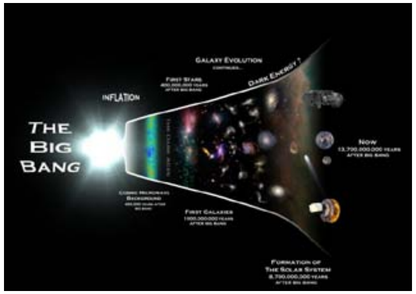
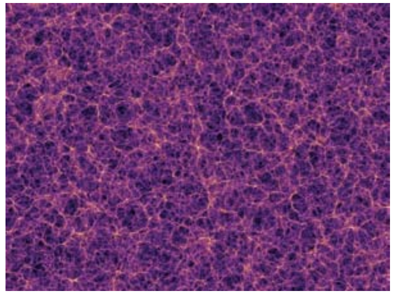
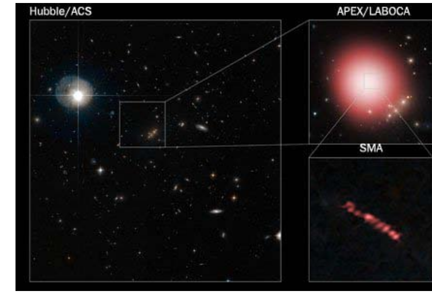
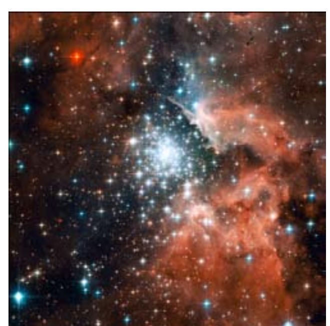






Massive Star Formation with ALMA Band 2

Steve Longmore
(ESO ALMA Fellow)



Outline

- Some key open questions in MSF:

- What do we need to learn to solve these questions?

- How will ALMA Band 2 help provide the answers?

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Some key open questions in MSF

- Q1: Where does the mass that eventually ends up on a massive star come from?

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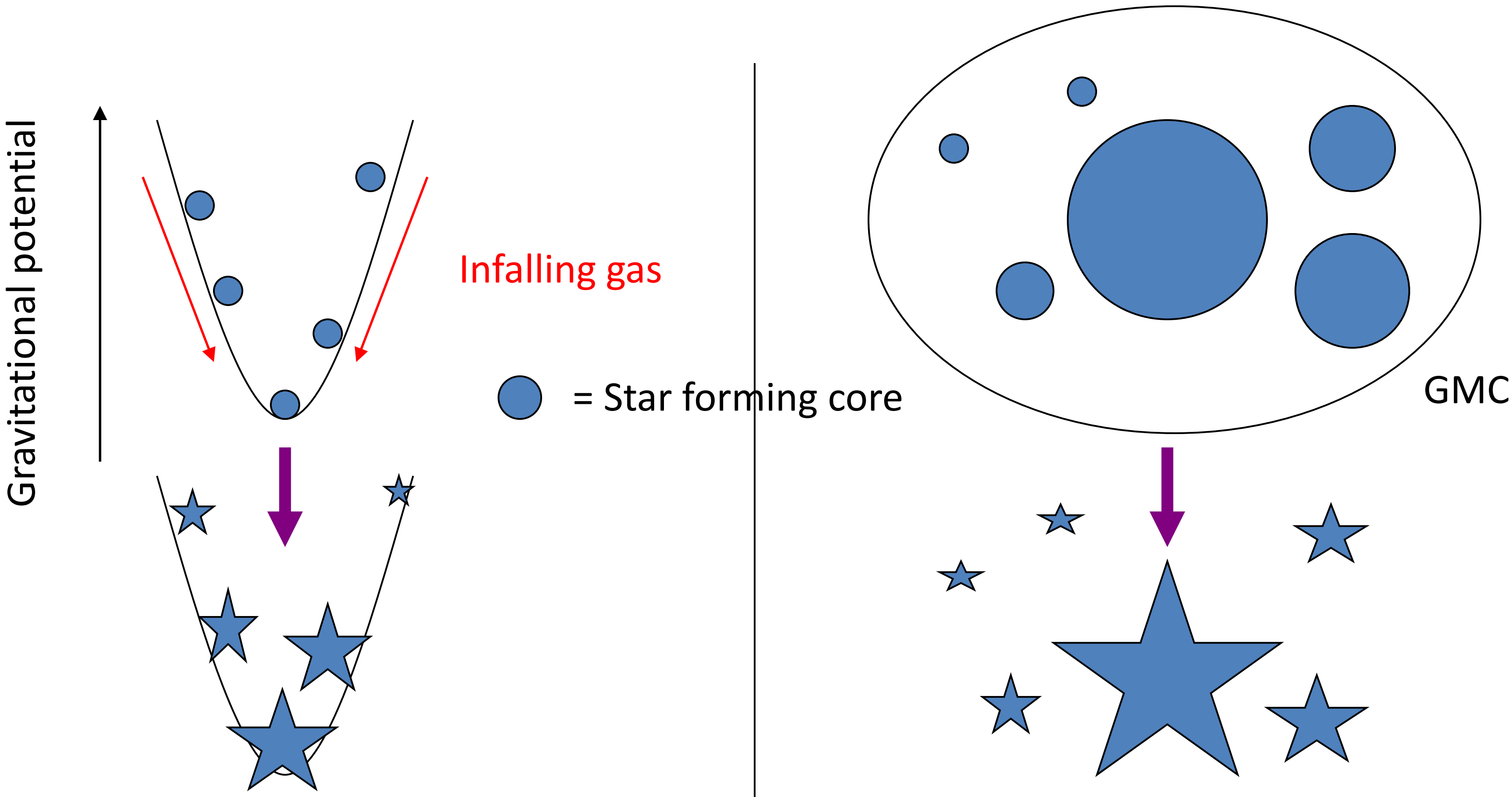

- Cores start at close to global Jeans mass.
- Those closest to cluster center accrete more mass.

- Initial conditions (eg turbulence)sets core mass function
- Final stellar mass largely set by initial core mass.
- Single core = Single stellar system

Some key open questions in MSF

- Q1: Where does the mass that eventually end up on a massive star come from?

- Q2: What is the affect of ionisation feedback?

Some key open questions in MSF

- Q1: Where does the mass that eventually end up on a massive star come from?

- Q2: What is the affect of ionisation feedback?
  - Triggering collapse of nearby dense cores?
  - Evaporate nearby envelopes/disks of lower mass star forming cores (e.g. proplyds)?
  - Halt accretion on to the massive star?
    - If so, how can you form O-stars? (See work by Keto & collaborators)
  - At what stage is ionisation important?
    - MSF requires high accretion rates to overcome radiation pressure
    - Hosokawa et al (2009): High accretion rates (>10^{-4} Msun/yr) cause "bloating" (R_* >100Rsun)
      - Delays hydrogen burning ➔ stars may not join ZAMS till ~40Msun
      - Less ionising photons than expected

Q2: What is the affect of ionisation feedback?

Peters et al, 2010, ApJ, 711, 101: Numerical simulations of massive star-forming cluster. Includes ionising radiation

Box side = 0.3pc

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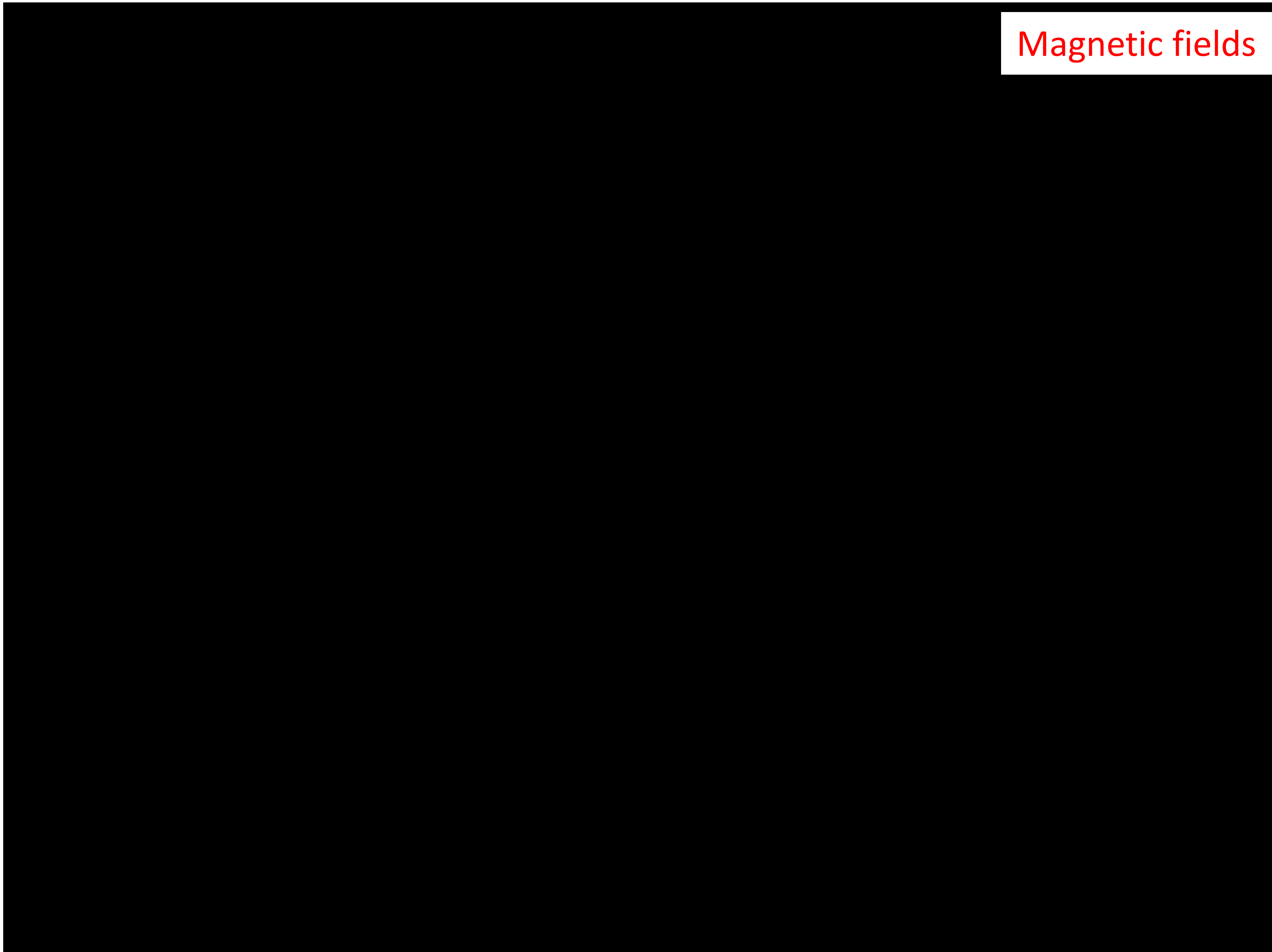

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- Q1: Where does the mass that eventually end up on a massive star come from?

A1: Initial conditions of both core fragments and cluster-scale gas

- Q2: What is the affect of ionisation feedback?

A2: Ionised gas properties and kinematics

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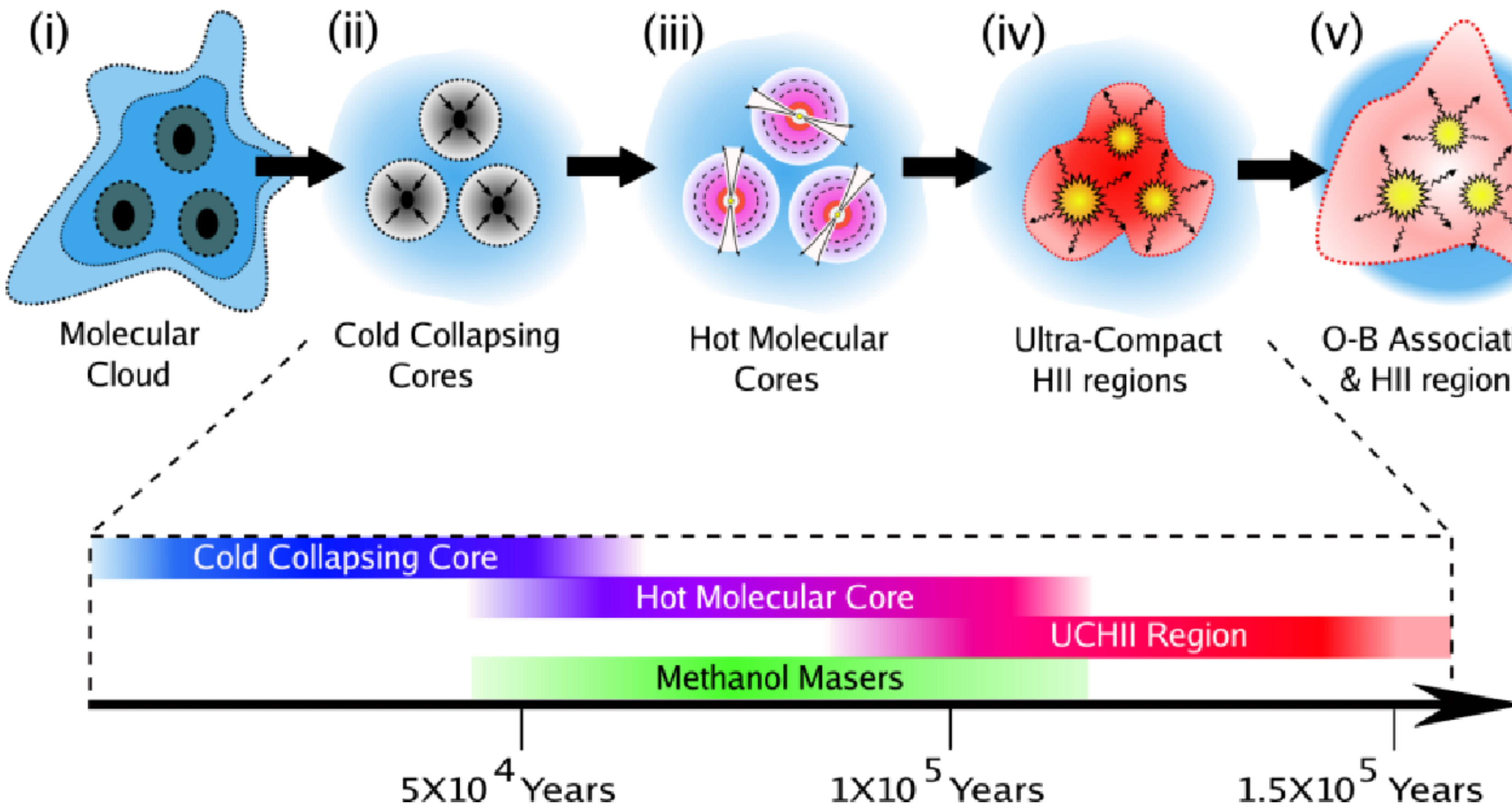
Lets start with what we know already…

Cartoon evolutionary sequence for massive star formation

Image credit: Cormac Purcell



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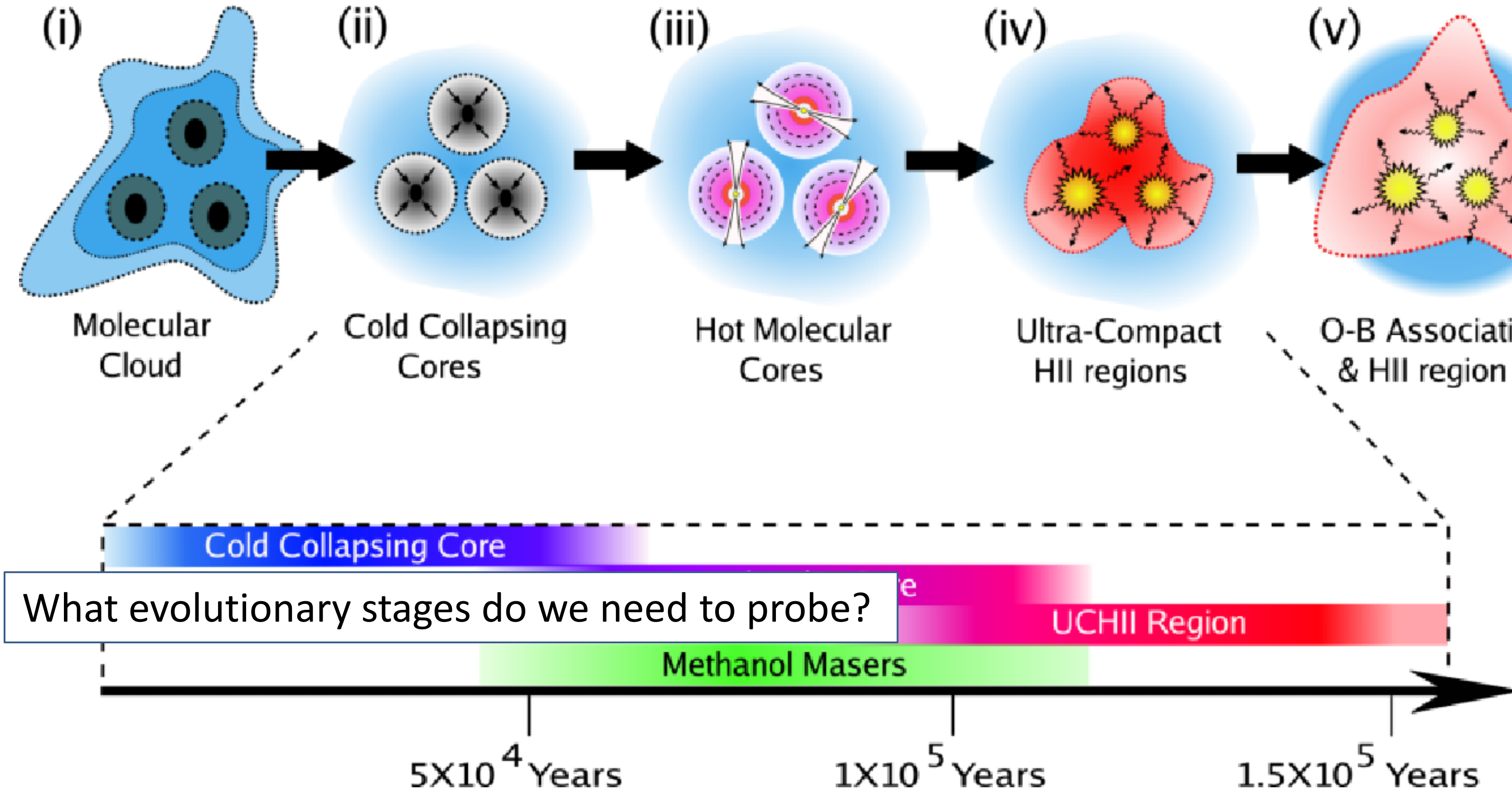

What evolutionary stages do we need to probe?

Cartoon evolutionary sequence for massive star formation

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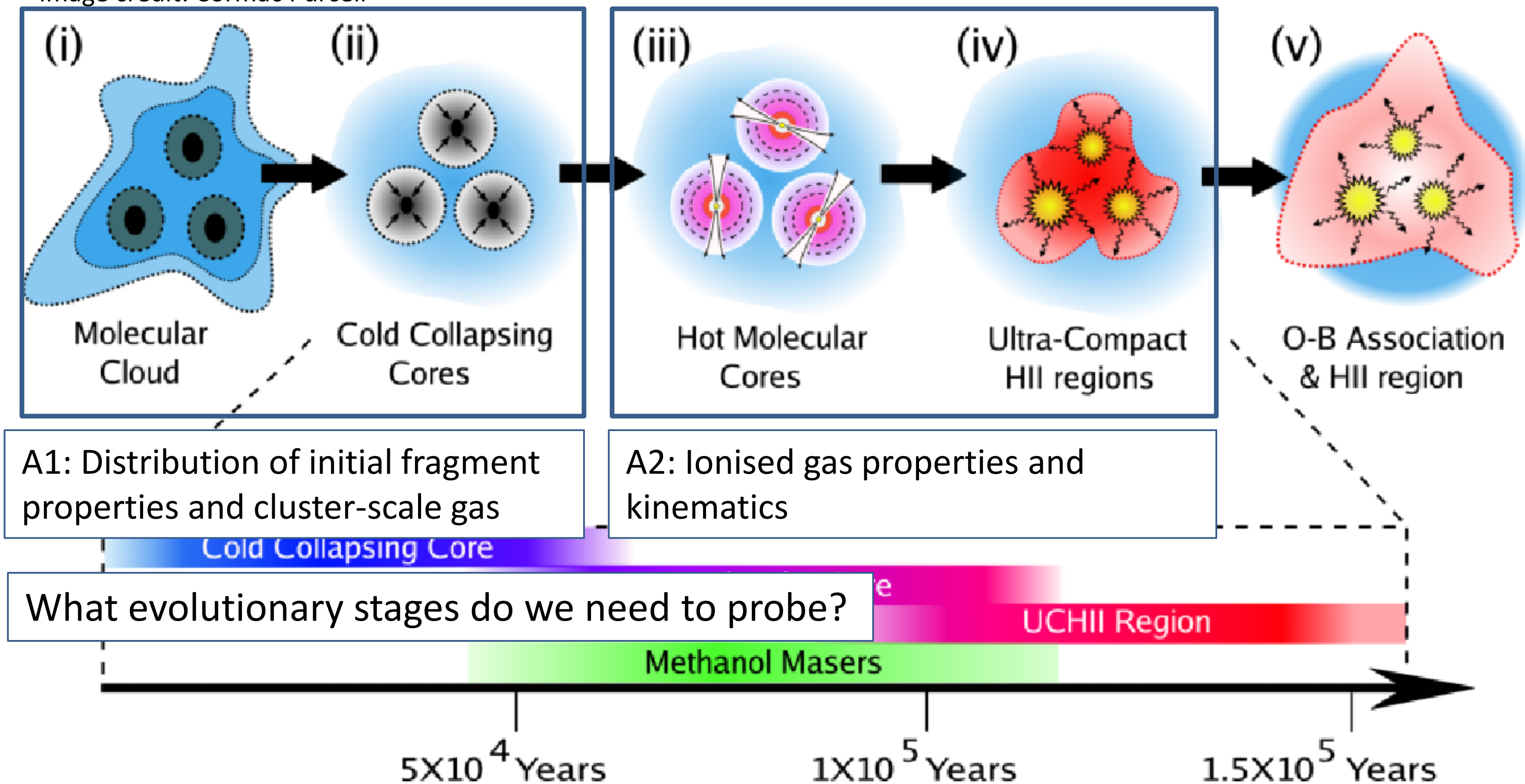

A1: Distribution of initial fragment properties and cluster-scale gas

A2: Ionised gas properties and kinematics

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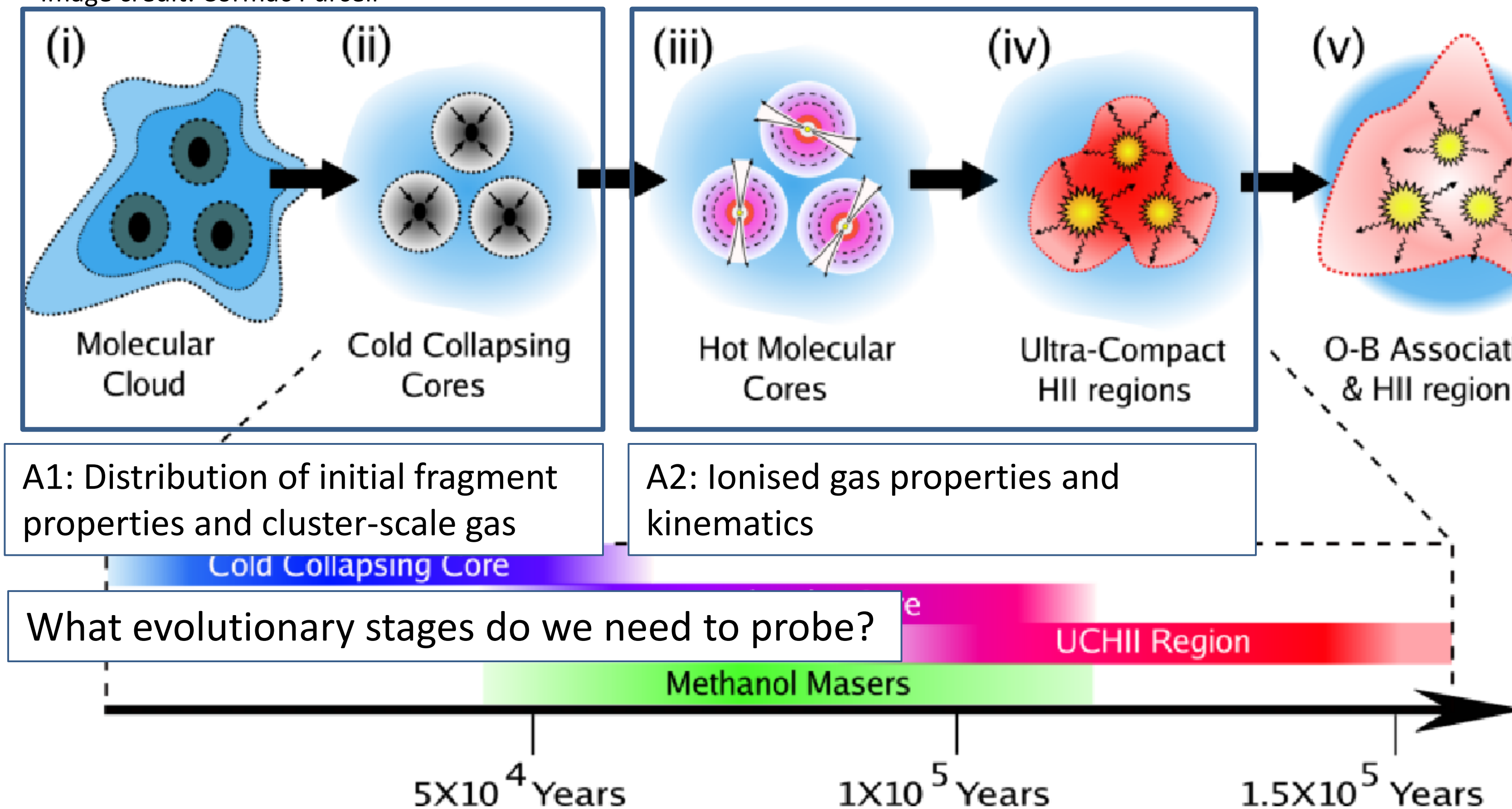

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Very short time scales:

➔ statistical approach needed to investigate affects of e.g. environmental conditions

➔ requires large samples at each evolutionary stage

Cartoon evolutionary sequence for massive star formation

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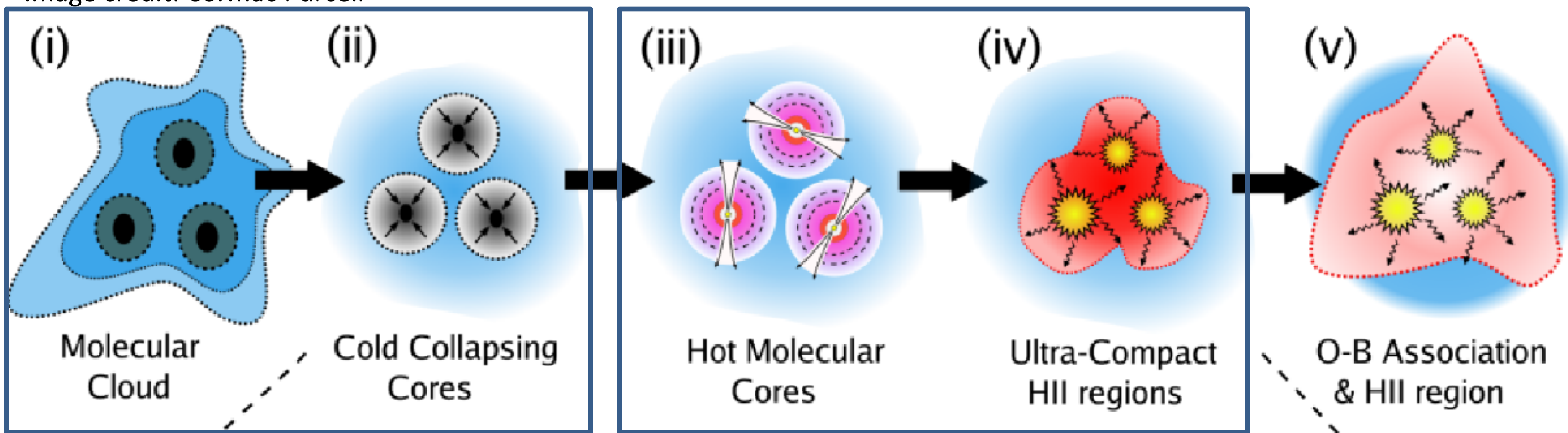

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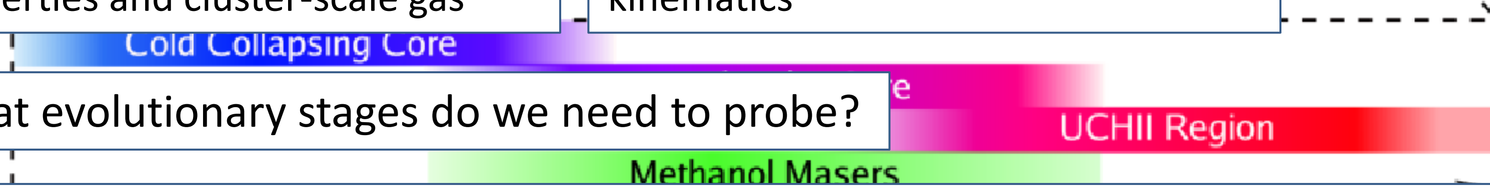


What evolutionary stages do we need to probe?

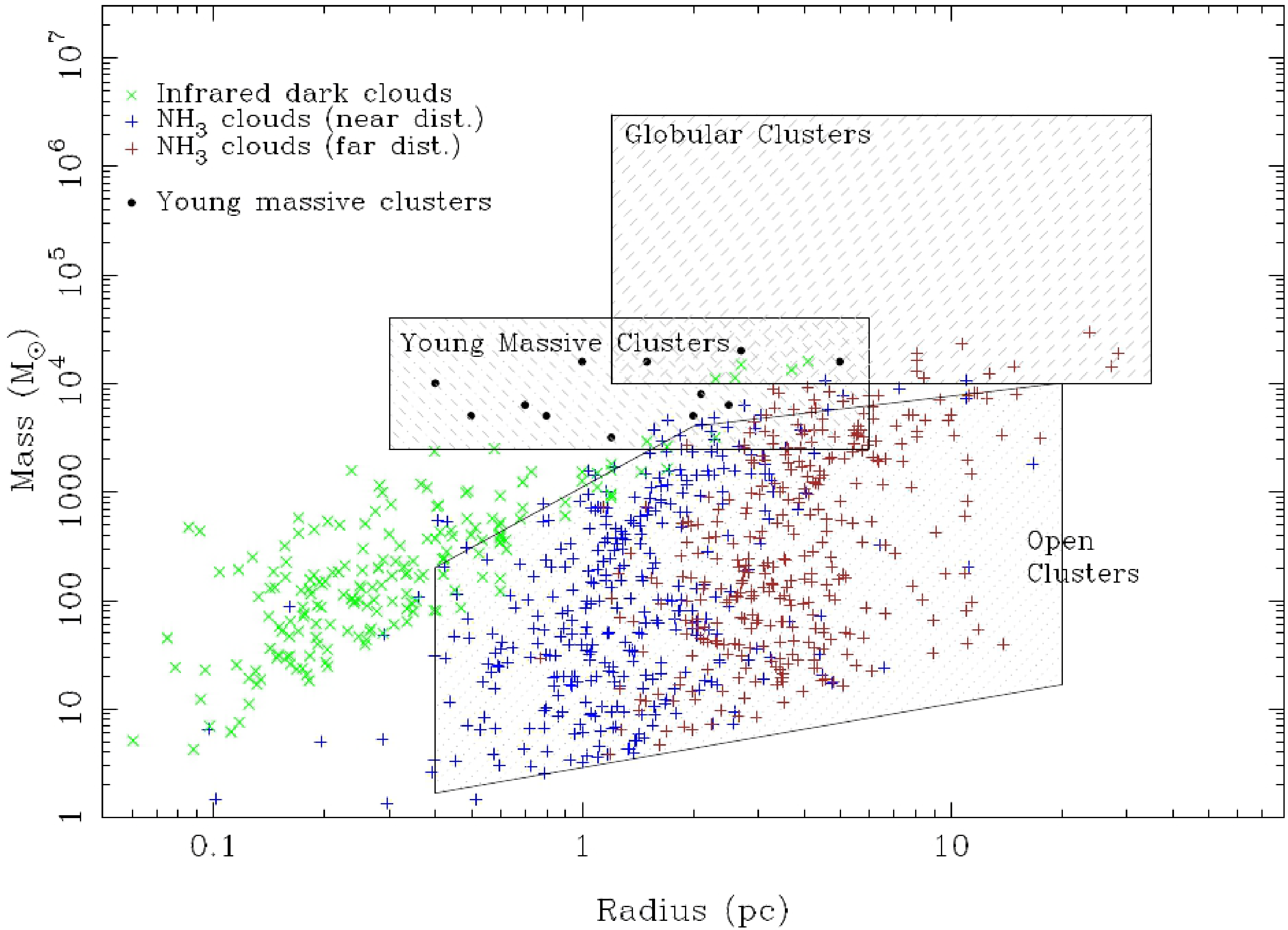
What are the observational requirements to sample both the formation scale of individual forming massive stars and the global cluster gas properties?

Very short time scales:

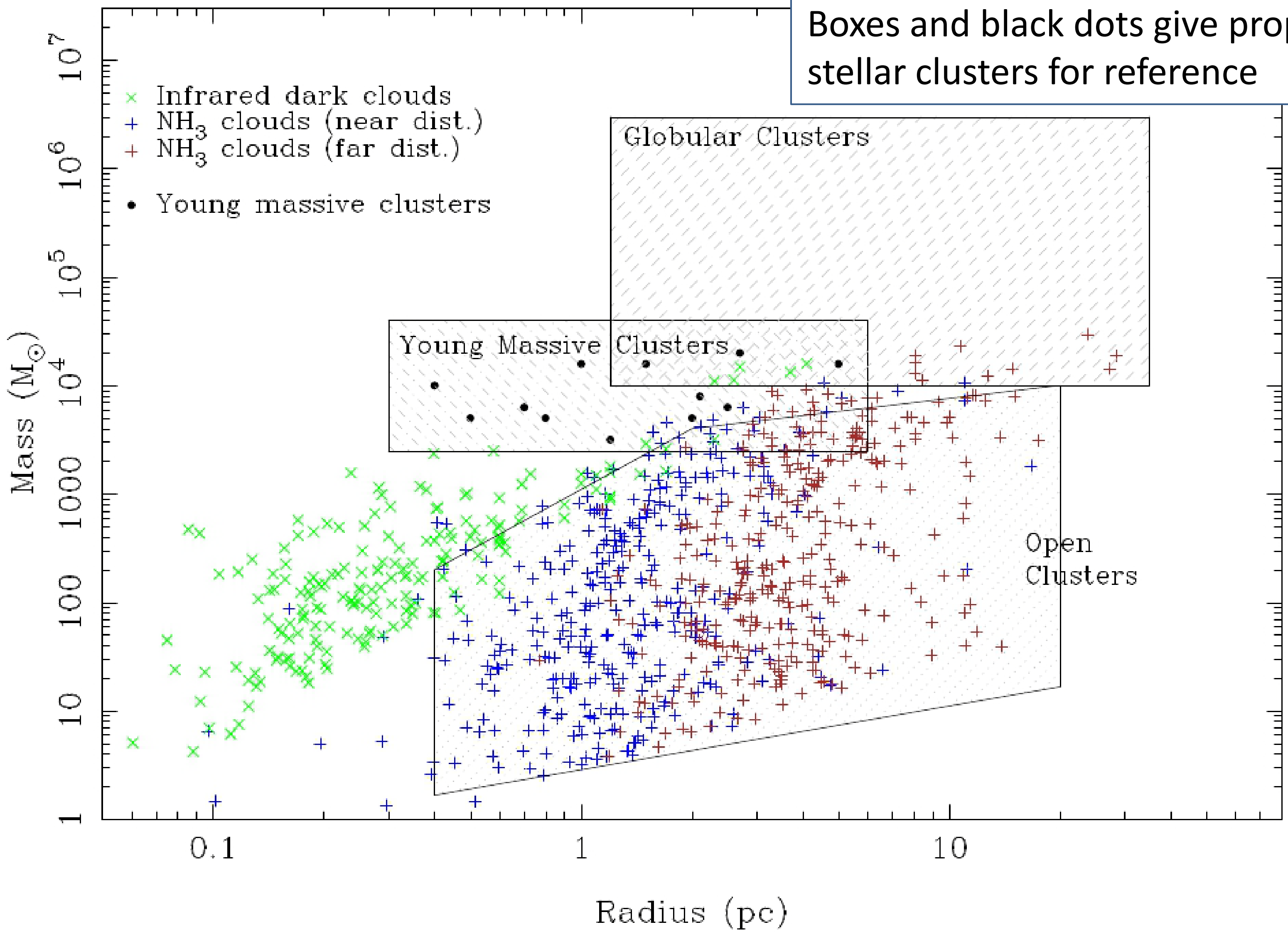
➔ statistical approach needed to investigate affects of e.g. environmental conditions

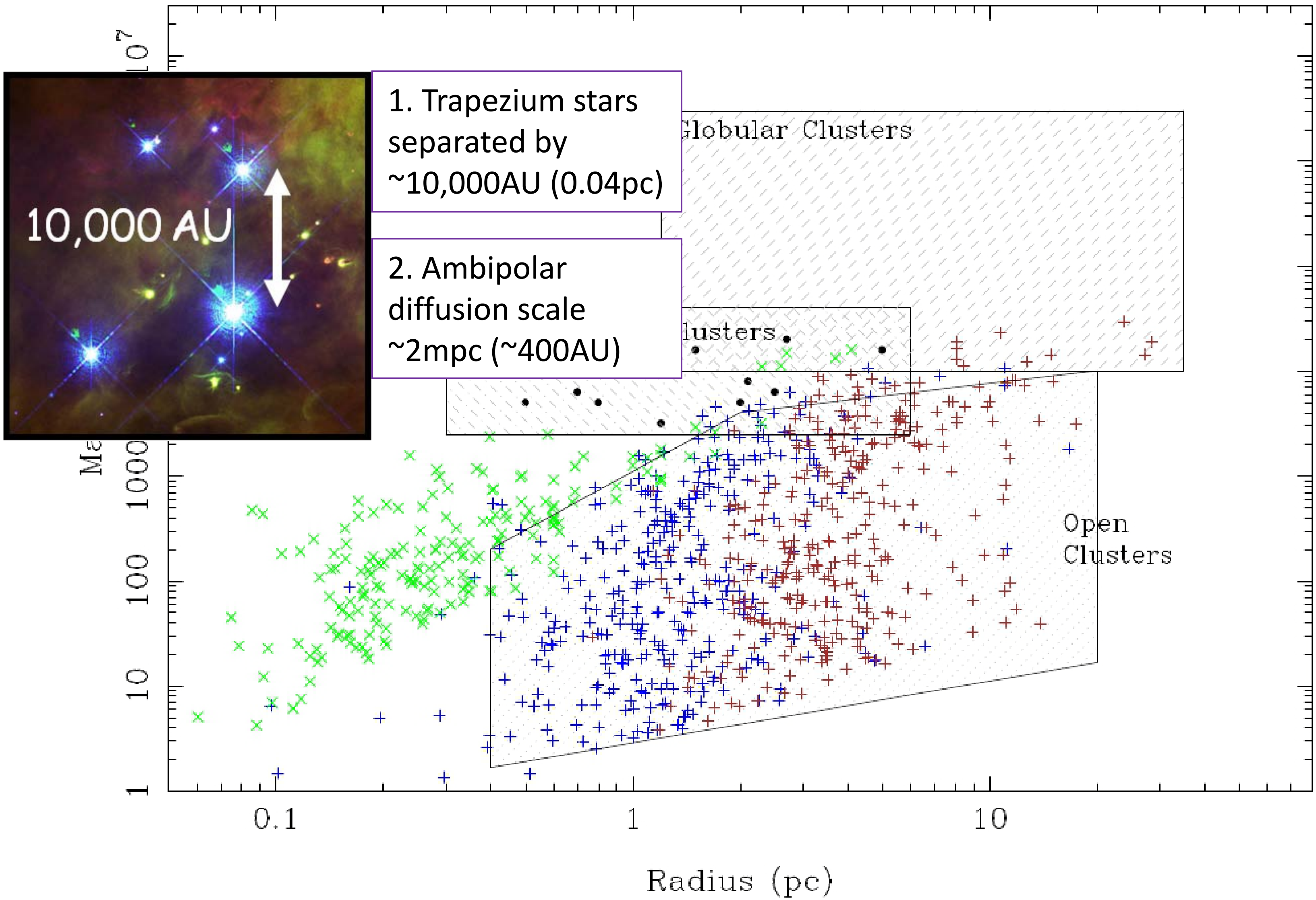
➔ requires large samples at each evolutionary stage

Many large surveys conducted to find massive protocluster progenitors (ATLASGAL, HiGAL, BGPS, MALT90, HOPS…).
Show results from two of these surveys: HOPS (Walsh et al 2008, 2011) and IRDCs (from Rathborne et al)



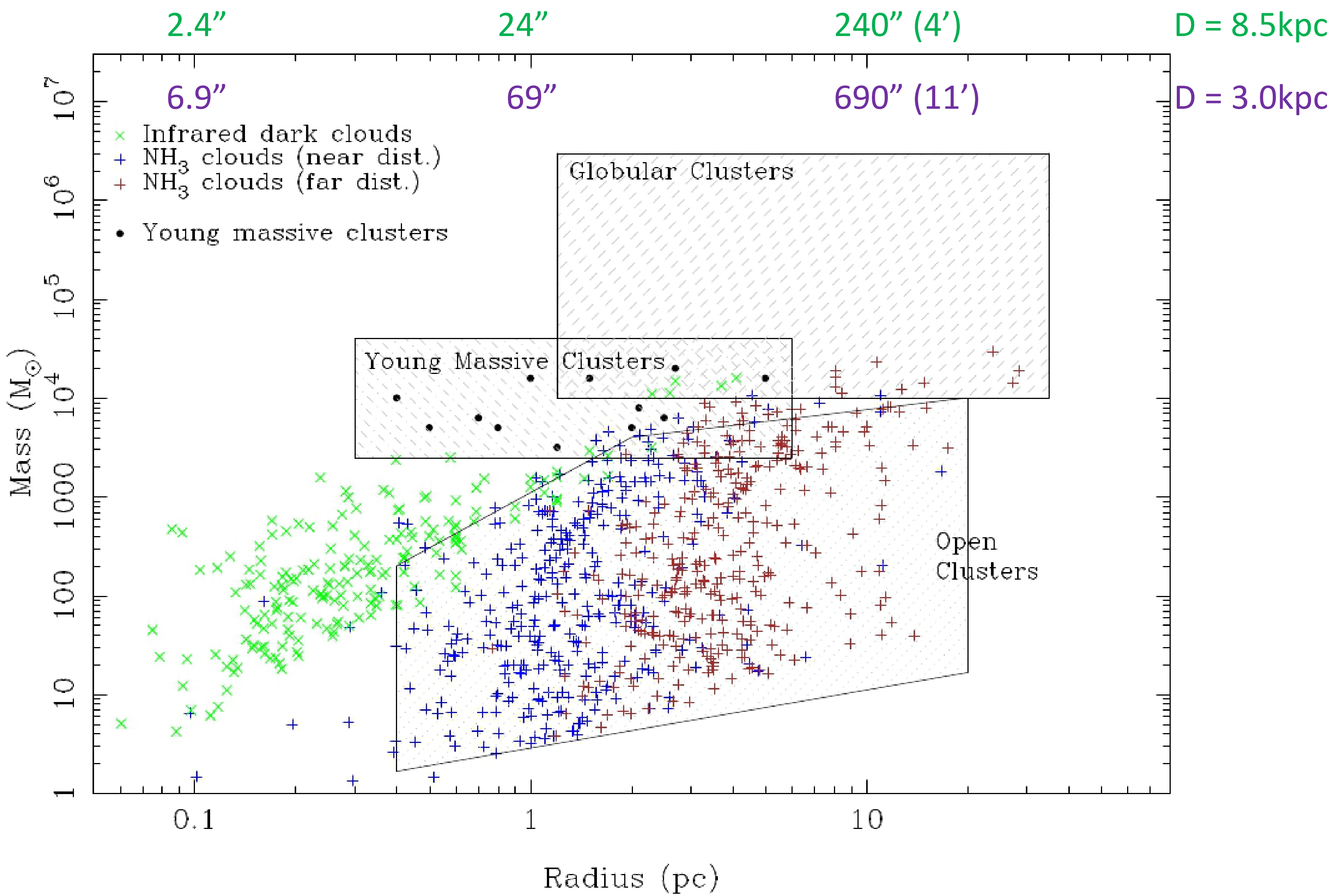
Colour-scale = gas and dust properties. Boxes and black dots give properties of stellar clusters for reference



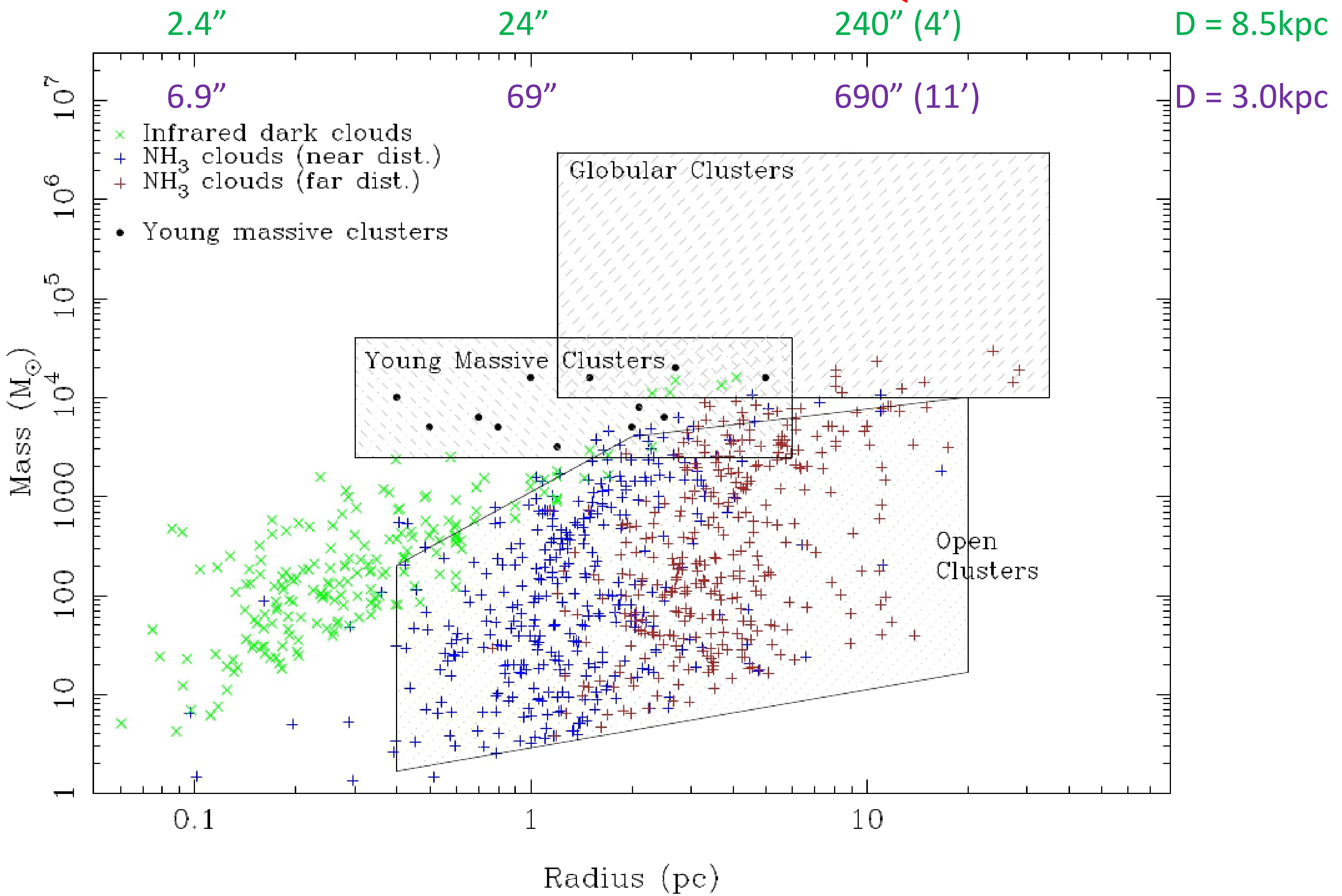


1. Trapezium stars separated by ~10,000AU (0.04pc)

2. Ambipolar diffusion scale ~2mpc (~400AU)


2.4”
24”
240” (4’)
D = 8.5kpc
6.9”
69”
690” (11’)
D = 3.0kpc
Infrared dark clouds
NH3 clouds (near dist.)
NH3 clouds (far dist.)
Young massive clusters
Globular Clusters
Young Massive Clusters
Open Clusters
Mass (M⊙)
Radius (pc)
0.1
1
10
1
10
100
1000
10^4
10^5
10^6
10^7

ALMA Primary beam: Band 2 = 80”, Band 9 = 9” ➔ ONLY WAY TO MAP FULL AREA OF LARGE NUMBER OF MASSIVE CLUSTERS WITH ALMA IS LOW FREQUENCIES



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Deuteration: a probe of the coldest and densest gas

deuteration processes:

1. $H_3^+ + HD \longleftrightarrow H_2D^+ + H_2 + \Delta E$
   needs low temperature
2. $NH_3 + H_2D^+ \longrightarrow \ldots\ldots \longrightarrow NH_2D + H$
   needs CO depletion

cold dense gas → lots of deuterated molecules

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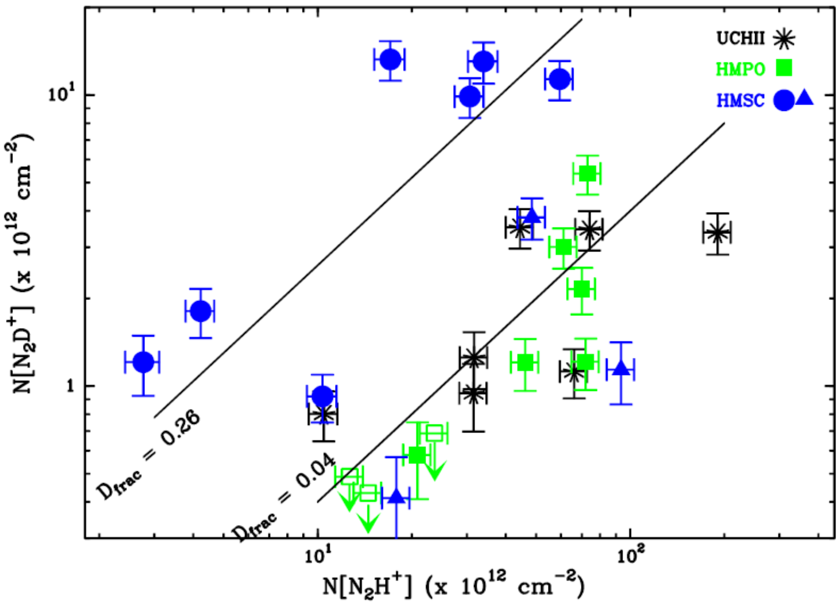

Fontani et al 2011, A&A, 529, 7

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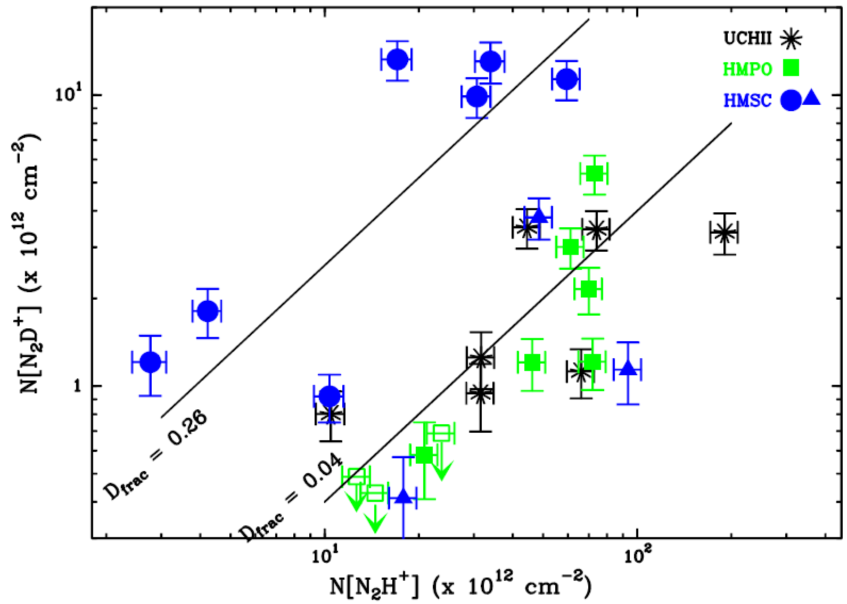

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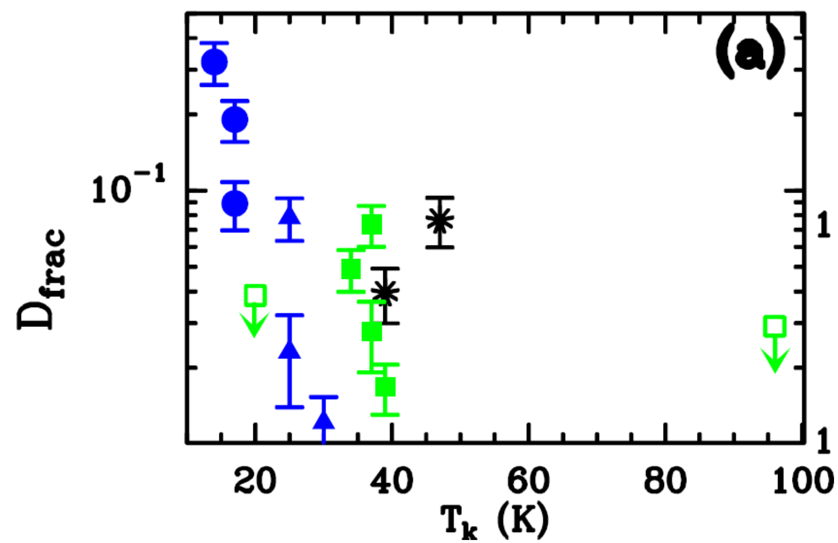

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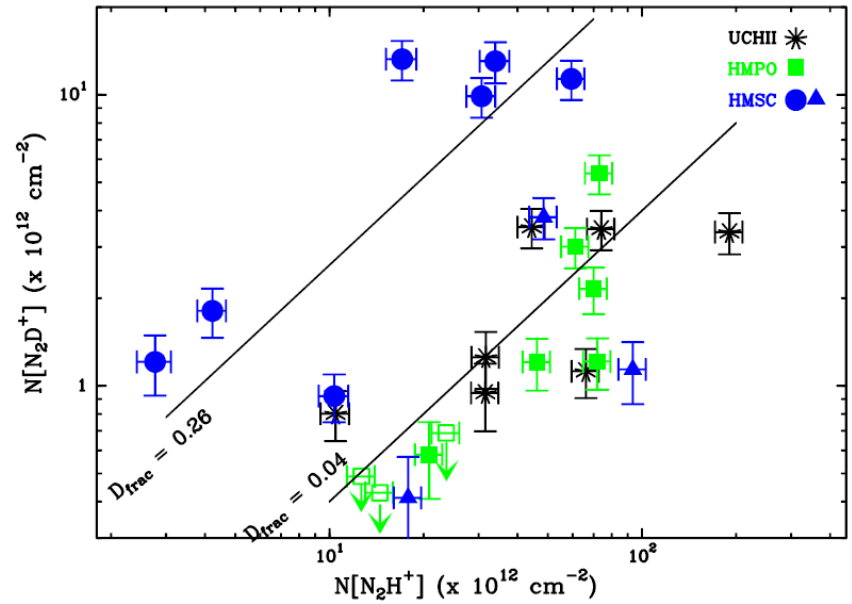

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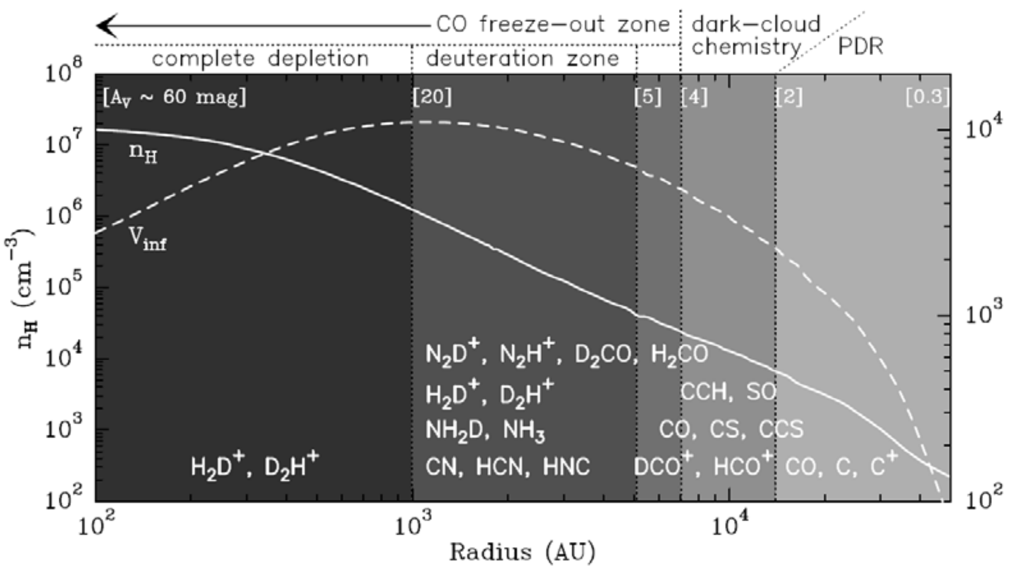
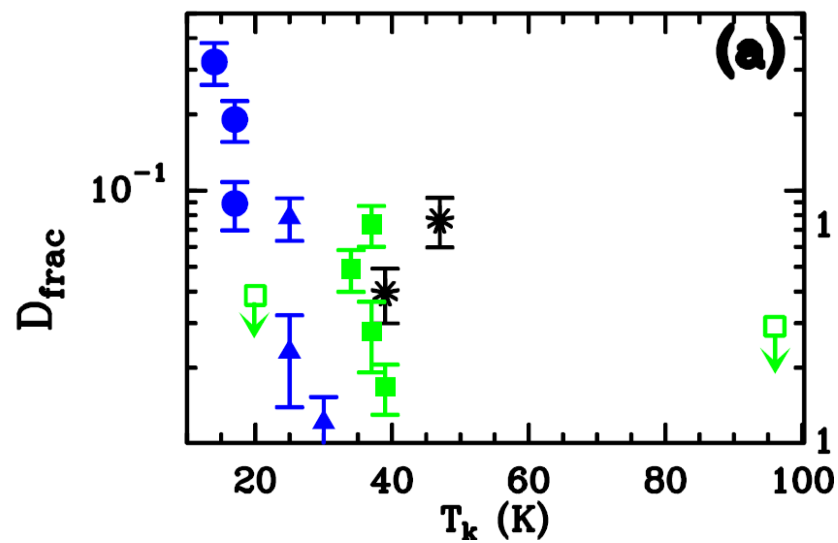
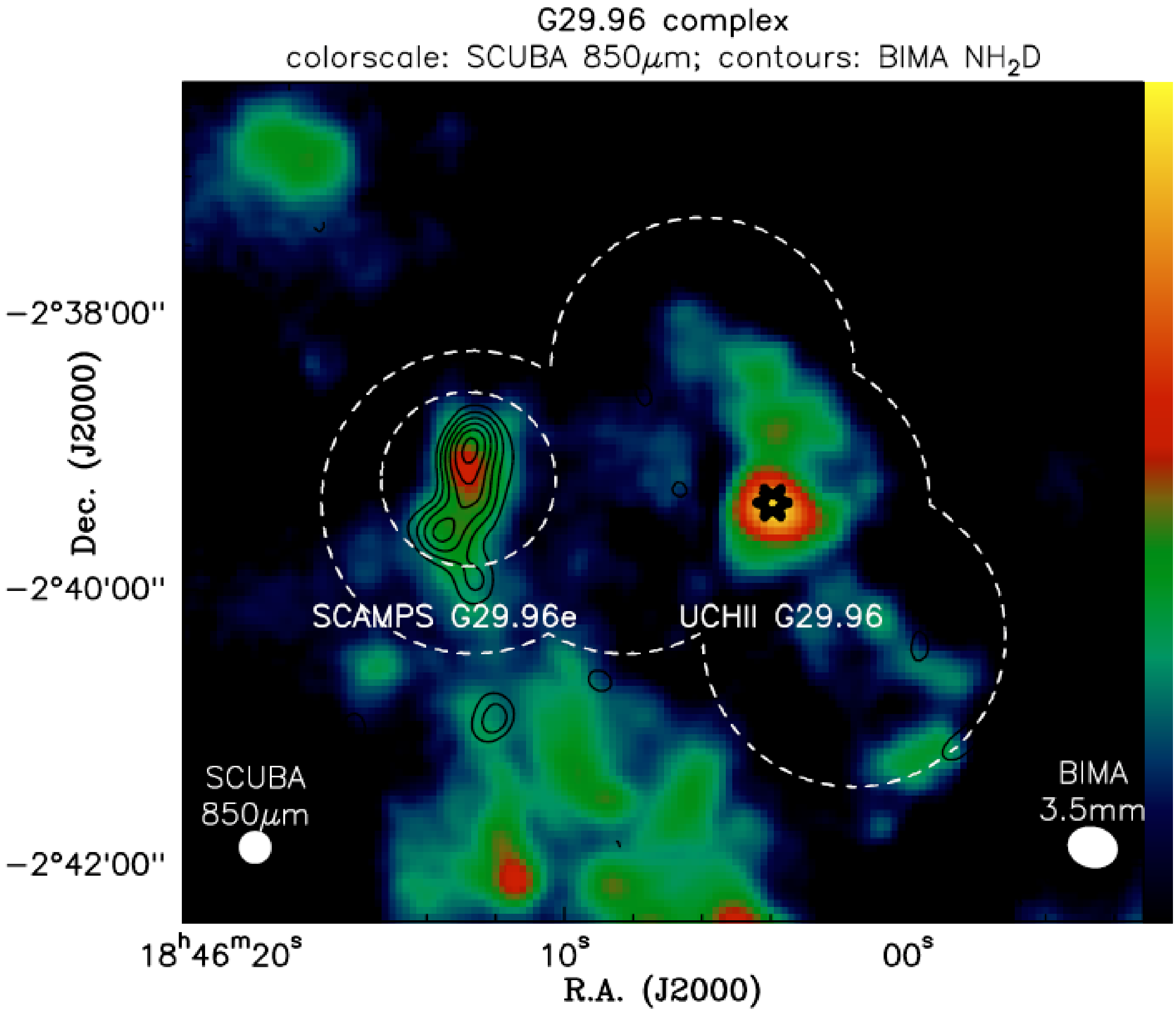


Caselli, 2011, IAU 280: Schematic representation of physical and chemical structure of pre-stellar, low-mass core



Pillai et al, 2011, A&A, 530, A118



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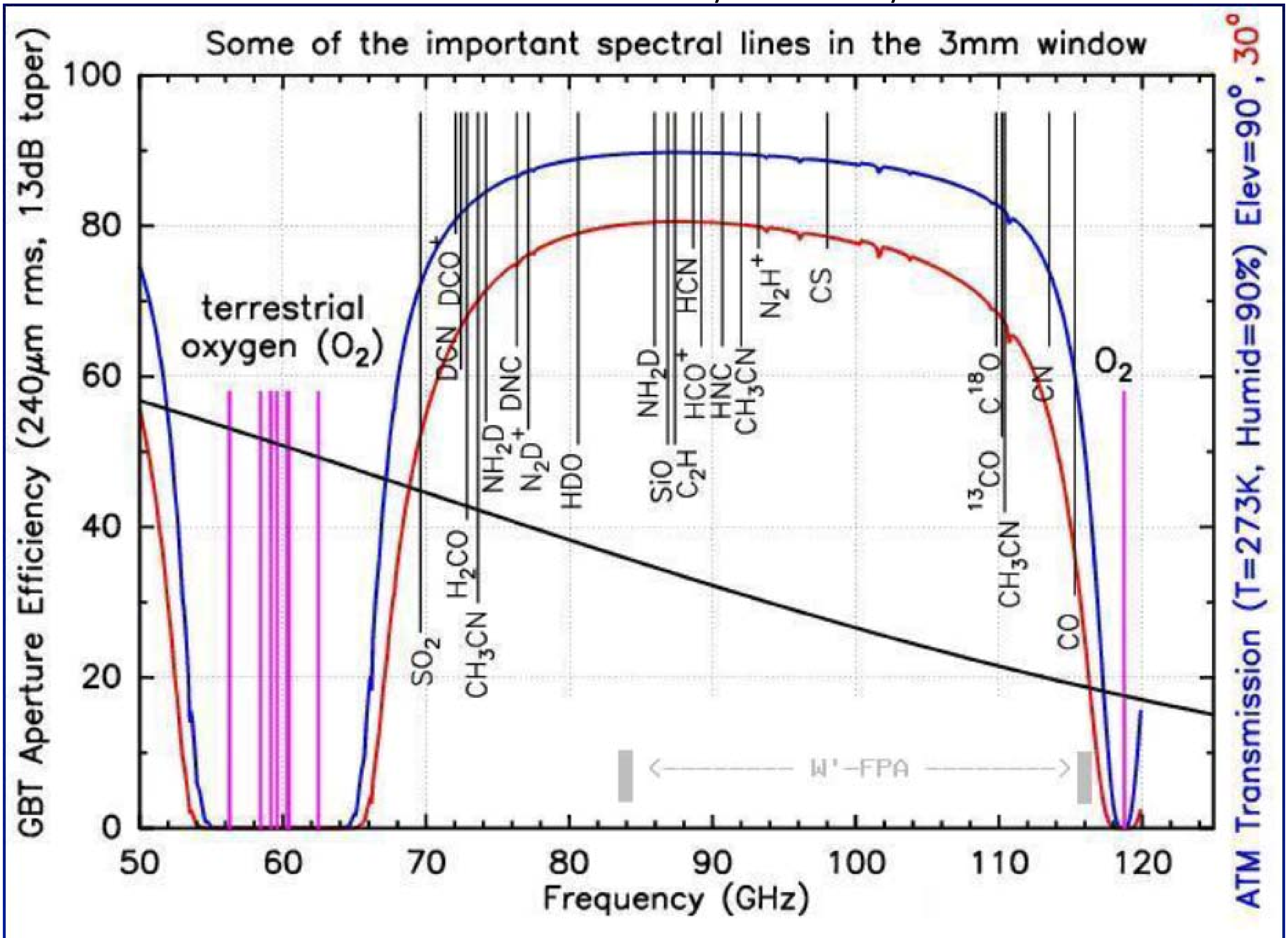

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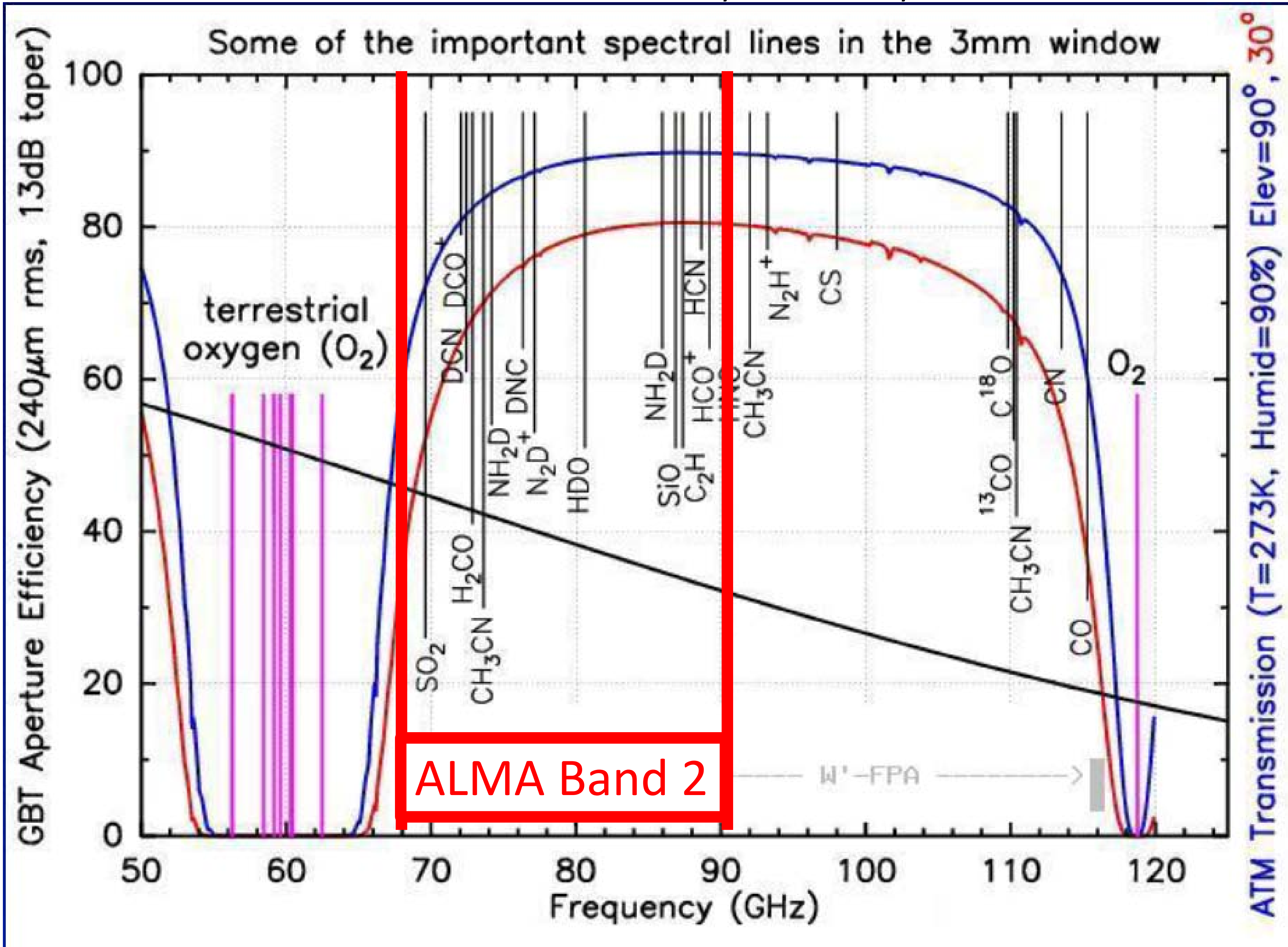

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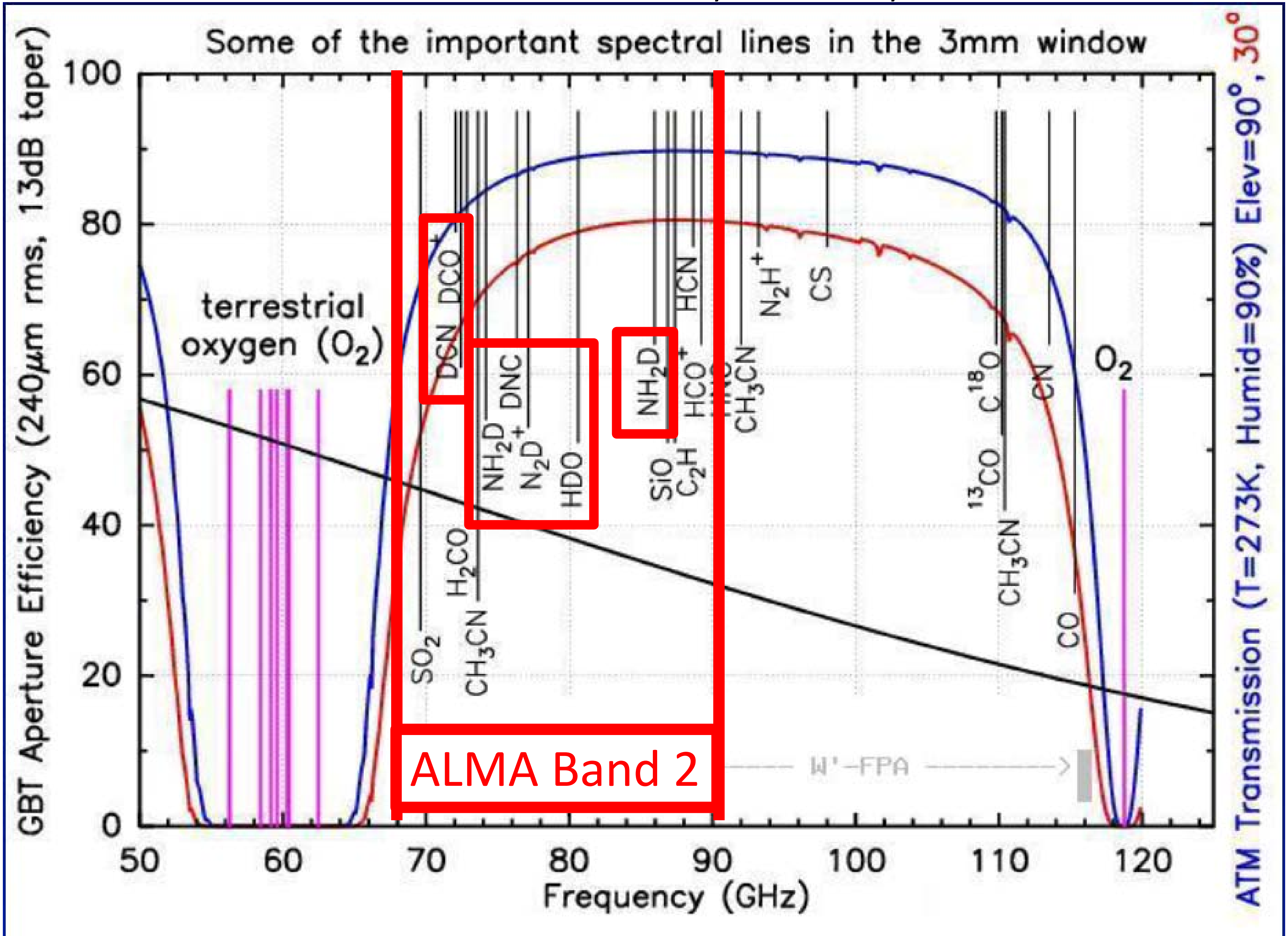

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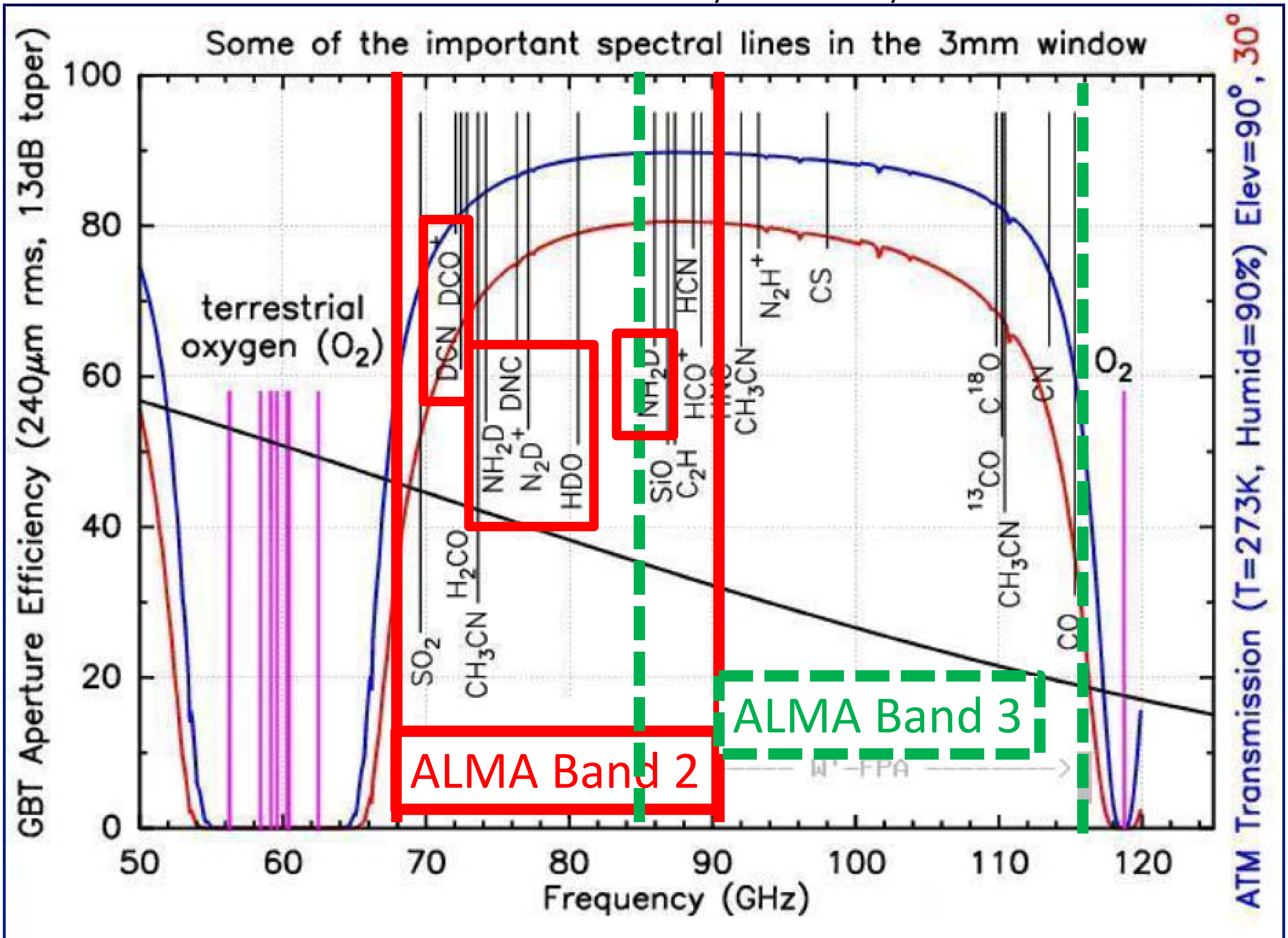

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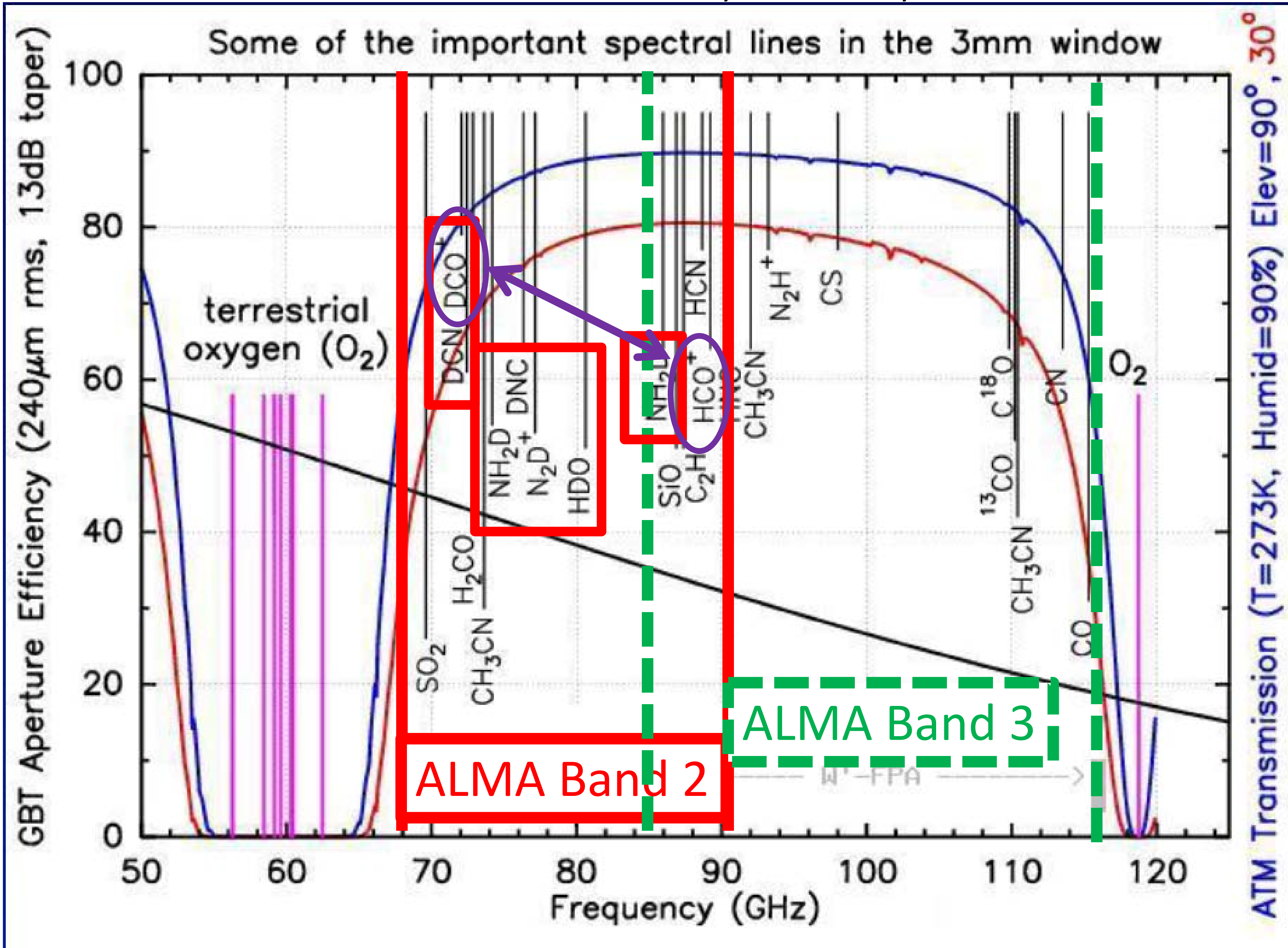

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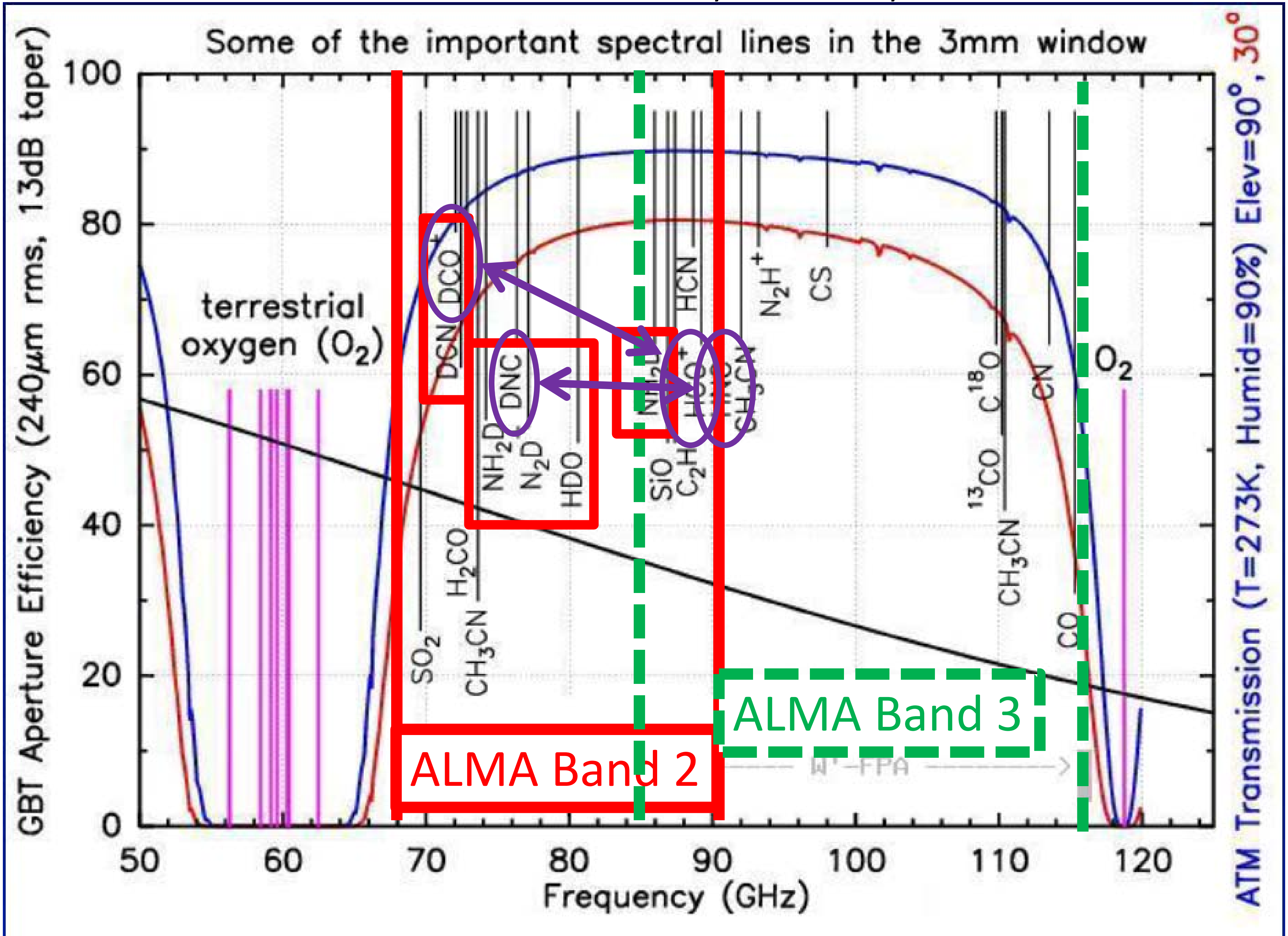

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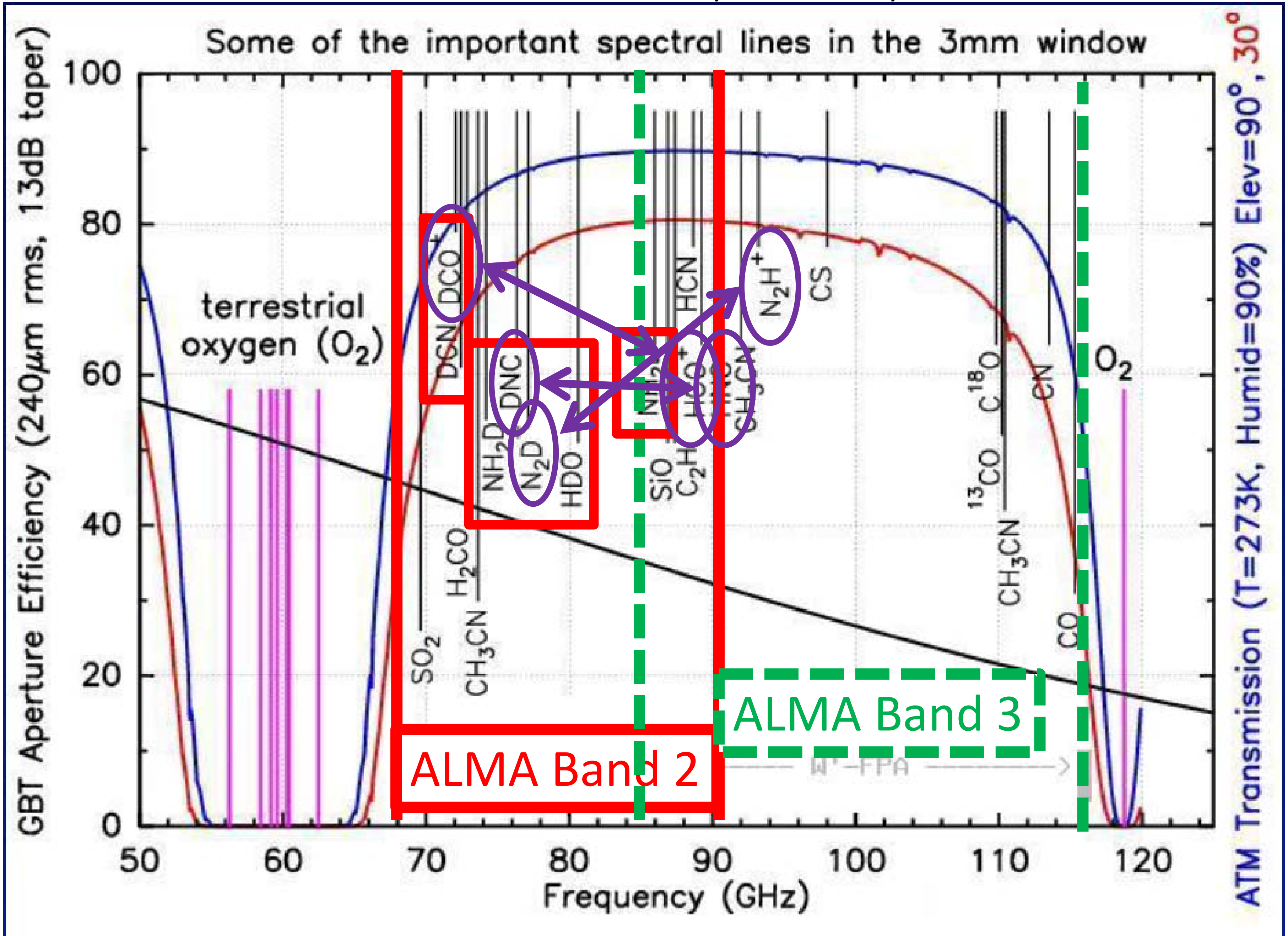

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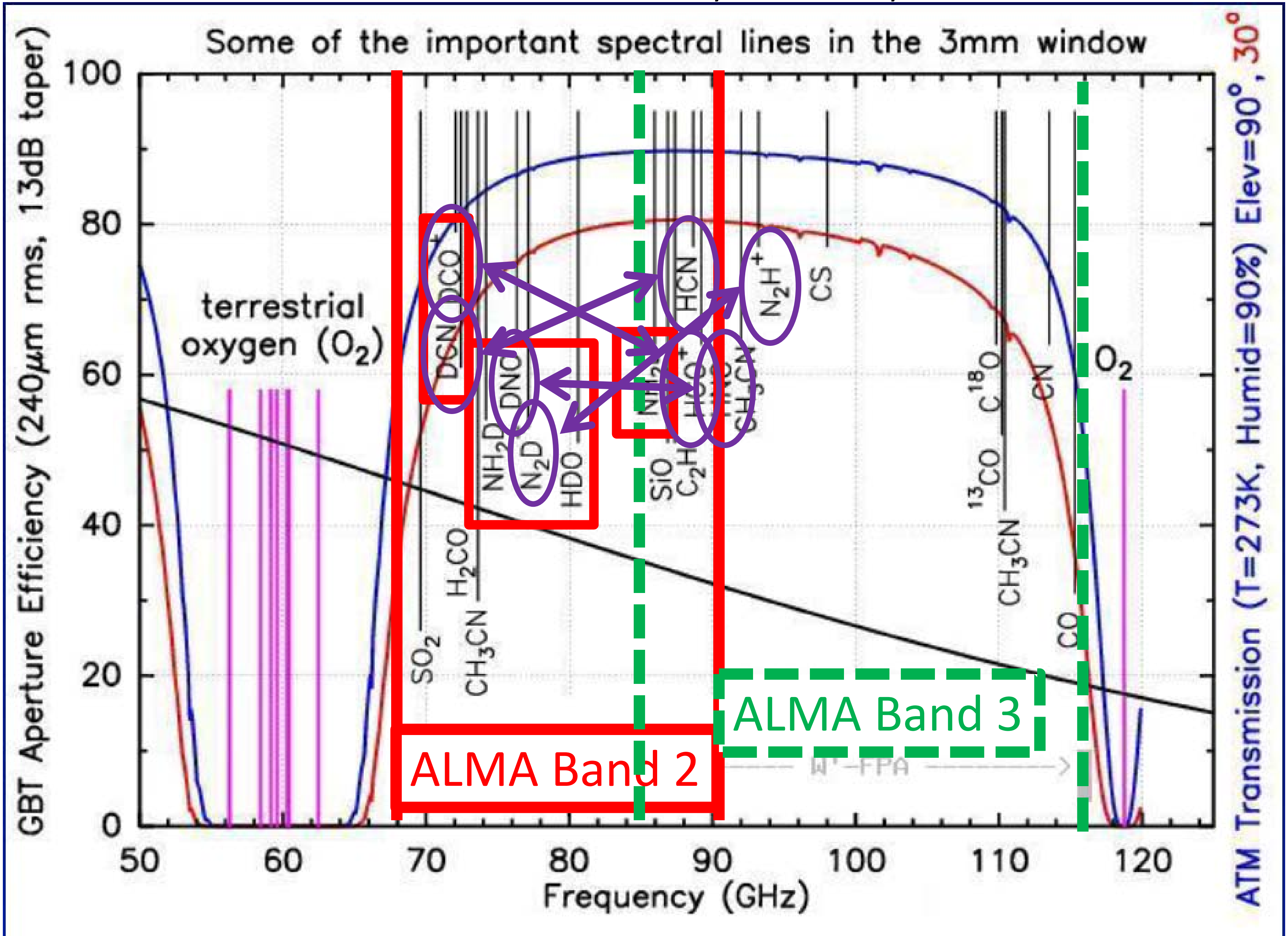

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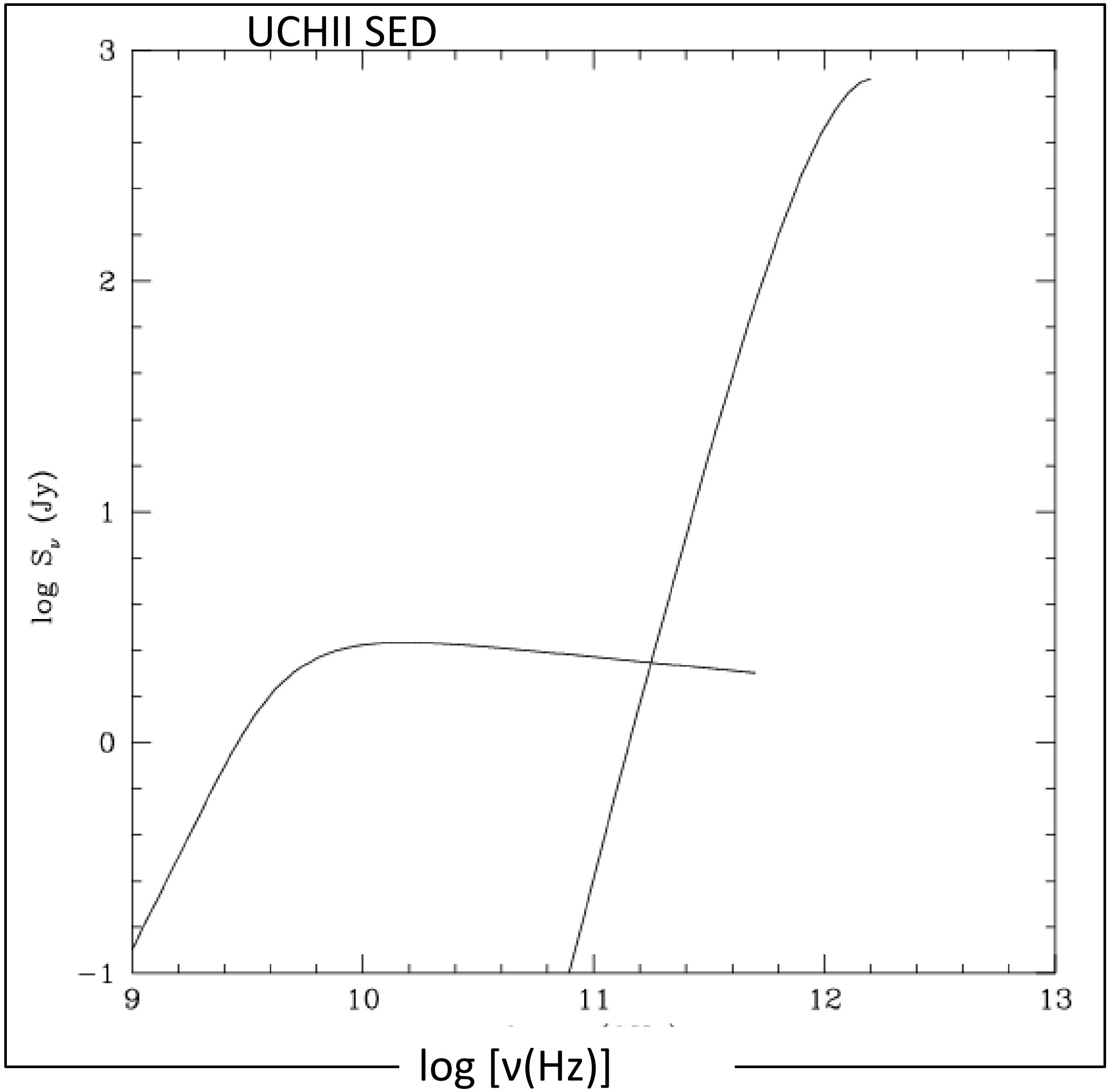
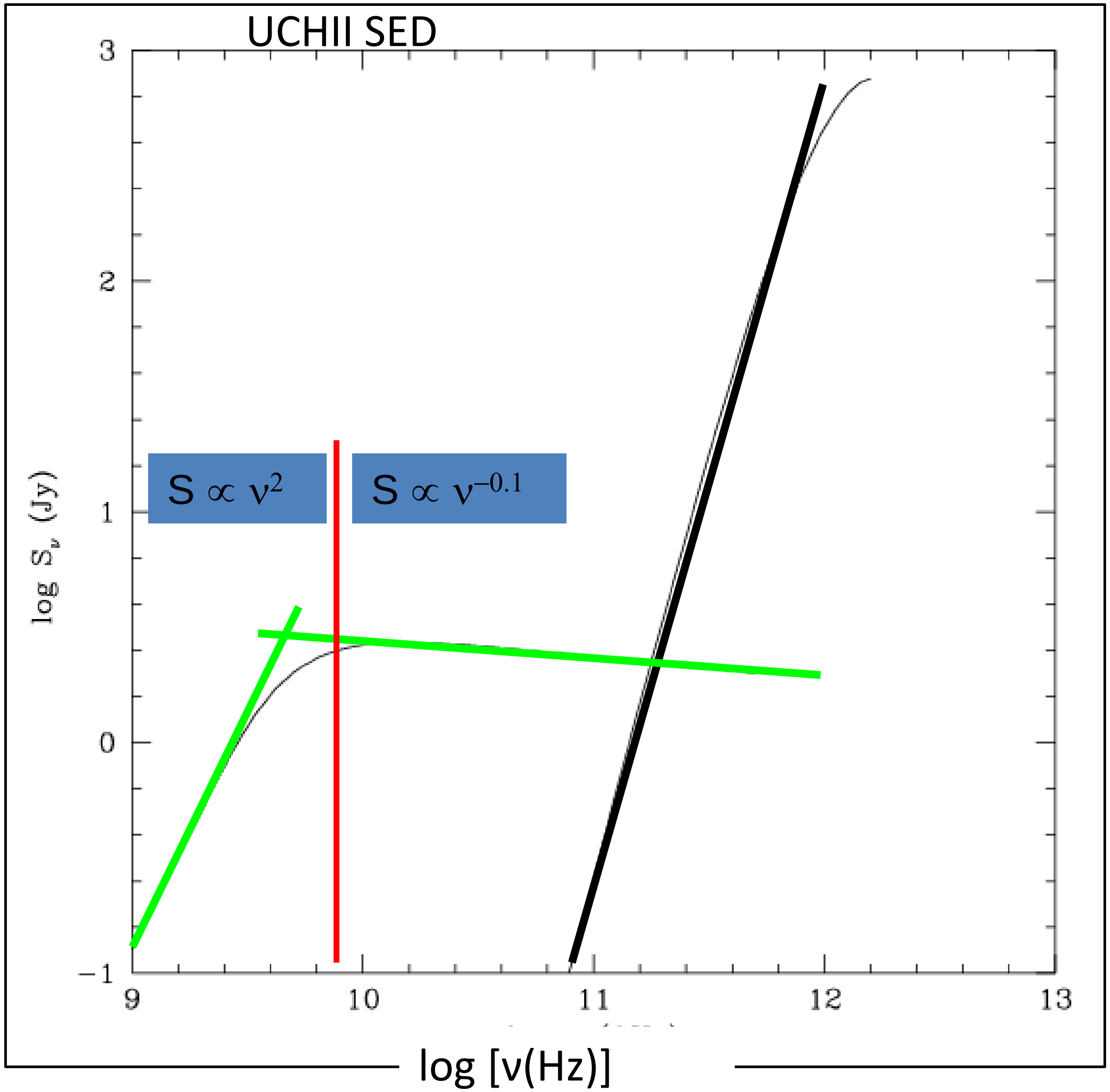
A2: Ionised gas properties and kinematics



- HII region thermal SED: 3 components
  - τ < 1 dust emission
  - τ < 1 free-free emission
  - τ > 1 free-free emission

A2: Ionised gas properties and kinematics



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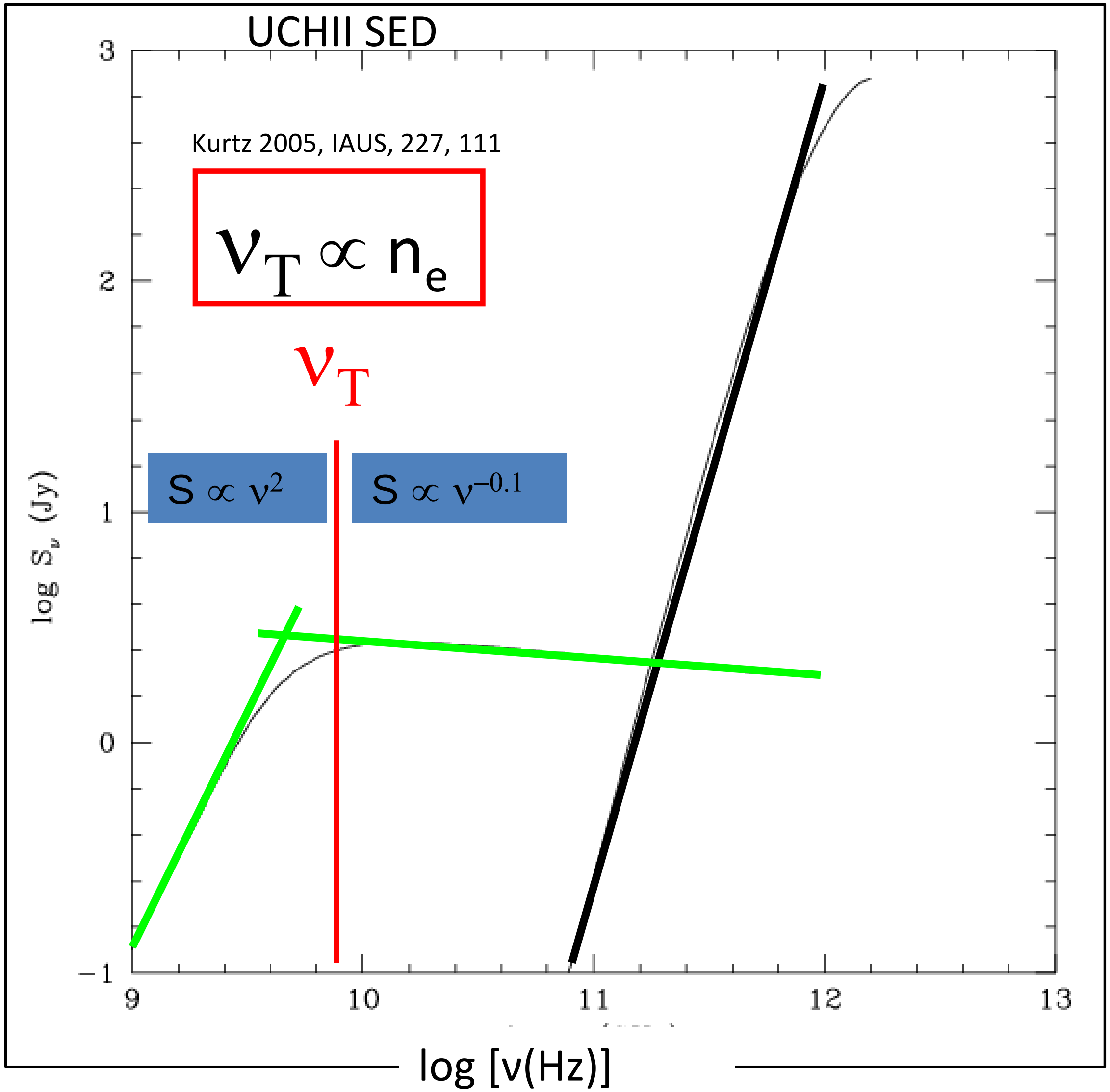

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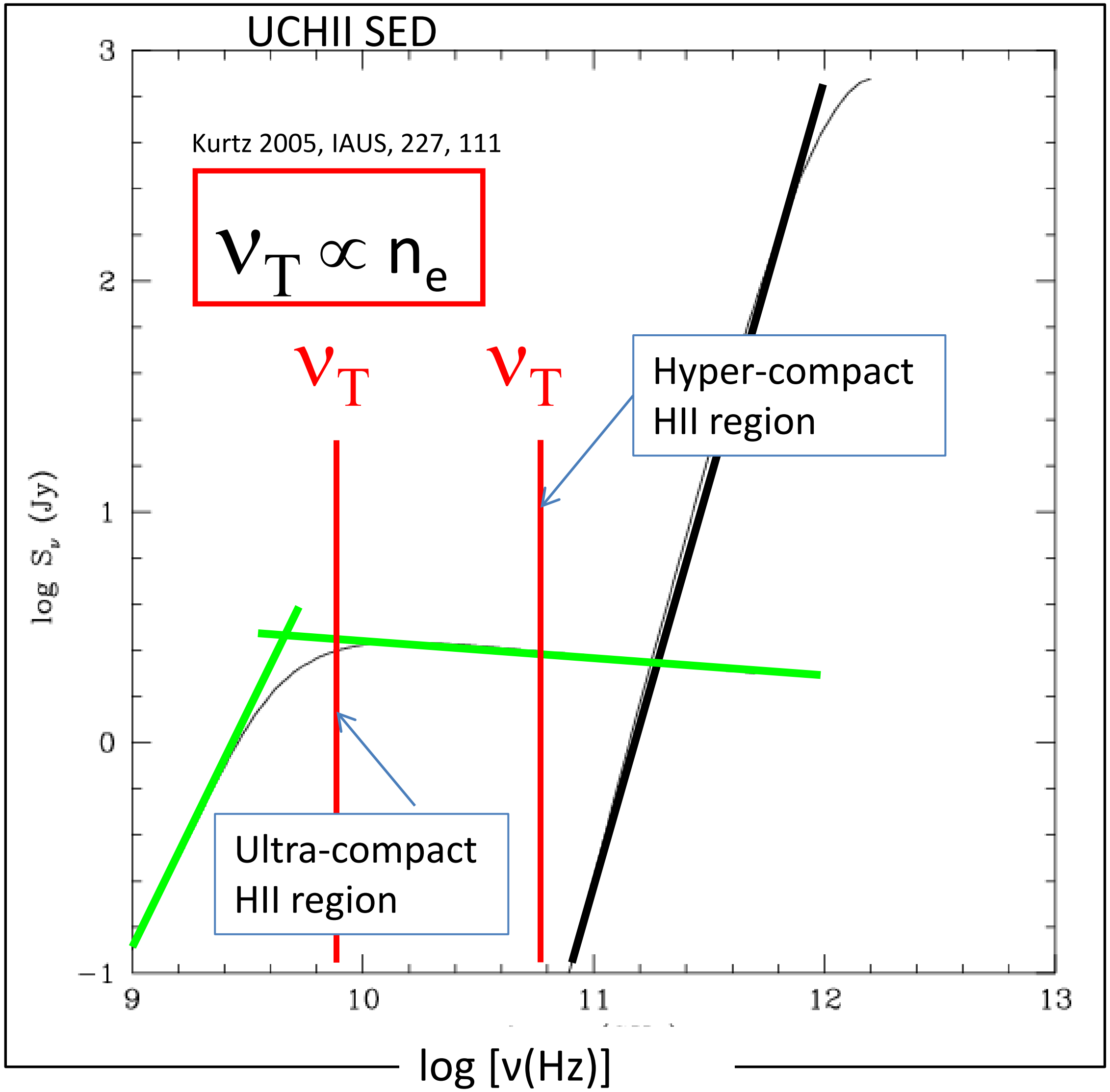

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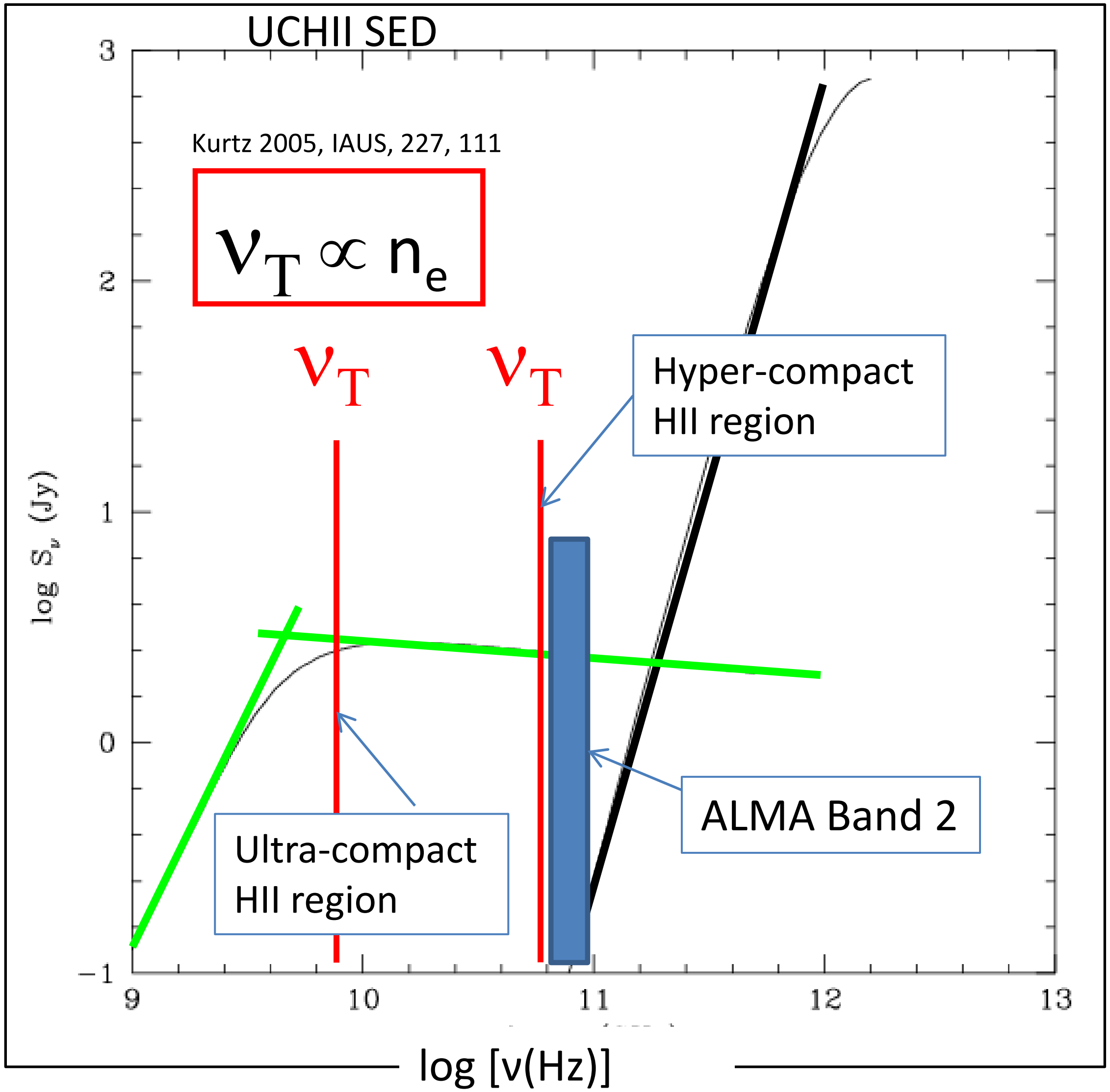

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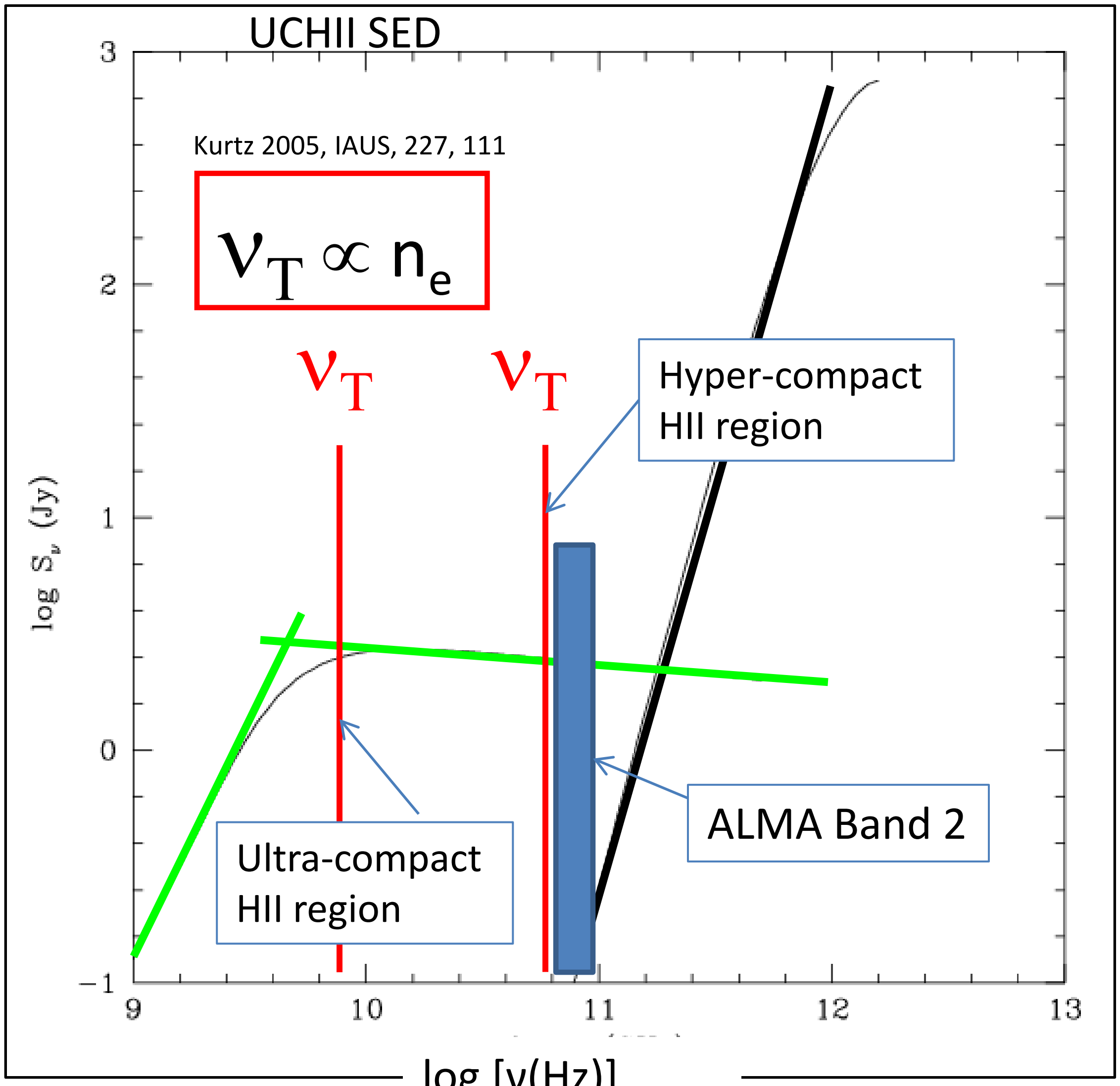
  - Minimal contamination from dust
  - Band width large enough to use spectral index to separate free-free and dust emission
  - Optimal frequency for detecting onset of ionisation in MSF regions

A2: Ionised gas properties and kinematics



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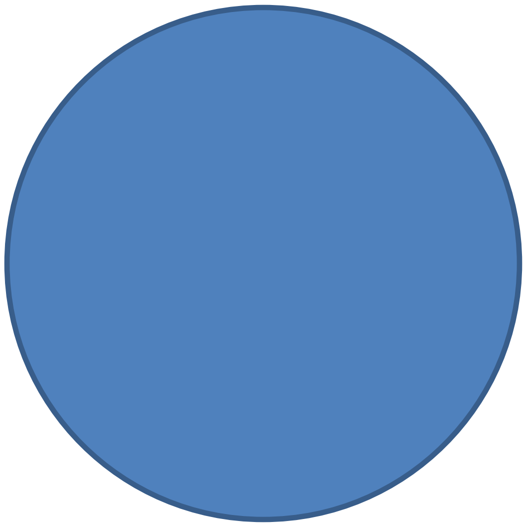
  - Optimal frequency for detecting onset of ionisation in MSF regions
- What about ionised gas kinematics?
  - Radio recombination lines

Synthetic ALMA RRL observations of a uniform, spherically symmetric HII region

R, $n_e(r)$, $T_e(r)$, $v(r)$



$$n_\mathrm{e} = \begin{cases} 28 \times \left(\frac{r}{\mathrm{pc}}\right)^{-2} \ \mathrm{cm}^{-3} & 0.02\,\mathrm{pc} \leqslant r \leqslant 0.1\,\mathrm{pc} \\ 0 & \text{otherwise,} \end{cases}$$

$$v_r = 25 \times \left(1 - \frac{r}{0.1\,\mathrm{pc}}\right) \mathrm{km\,s^{-1}}$$

$T_e = 10^4$ K

Peters, Dullemond & Longmore (in preparation)

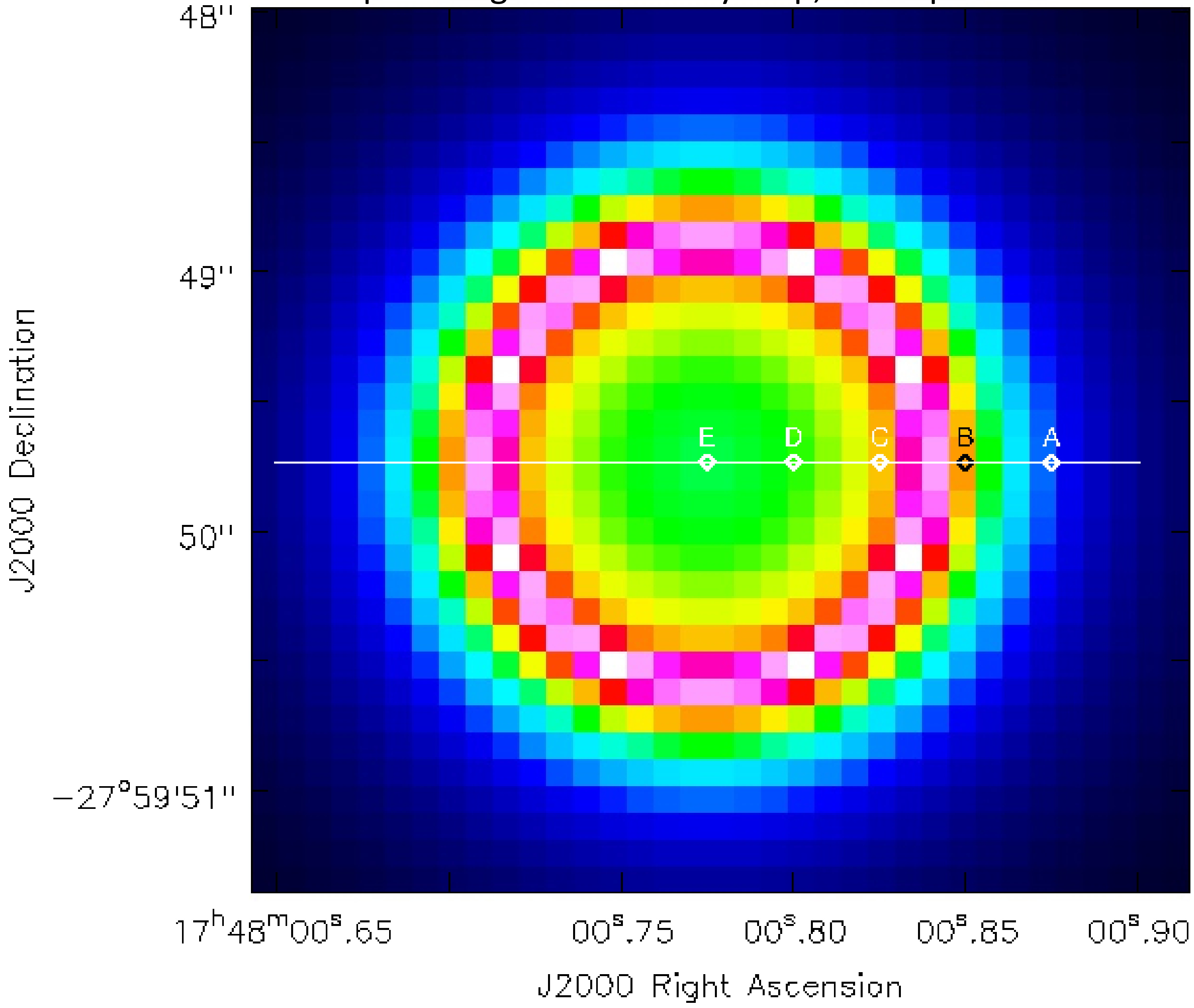
1. Generate synthetic HII regions

2. Non-LTE radiative transfer modelling of RRL and continuum emission

3. Create synthetic sky emission maps for sources scaled to different distances

3. Simulate observing with ALMA (*SIMDATA*)

H68alpha integrated-intensity map, D = 3kpc



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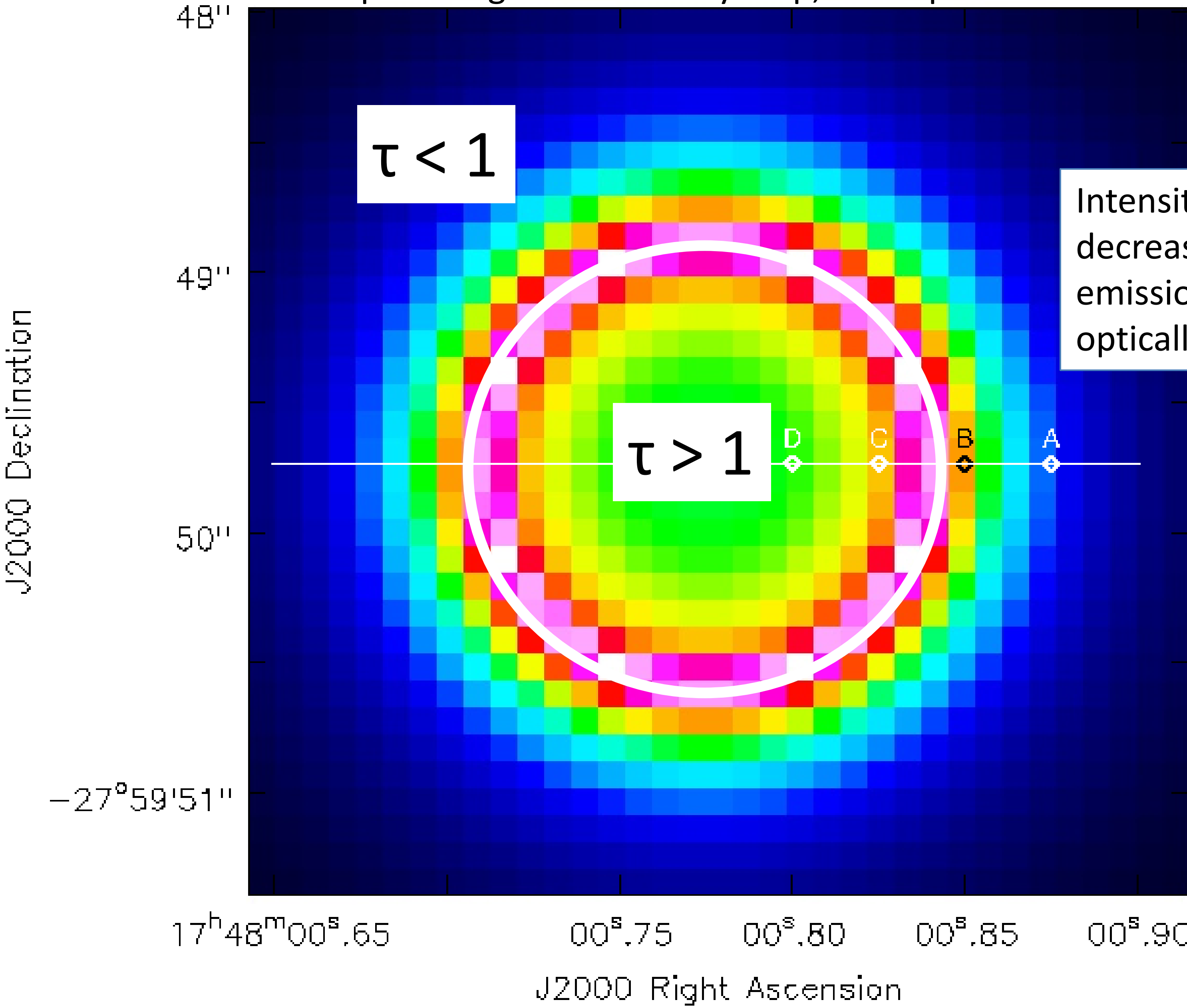
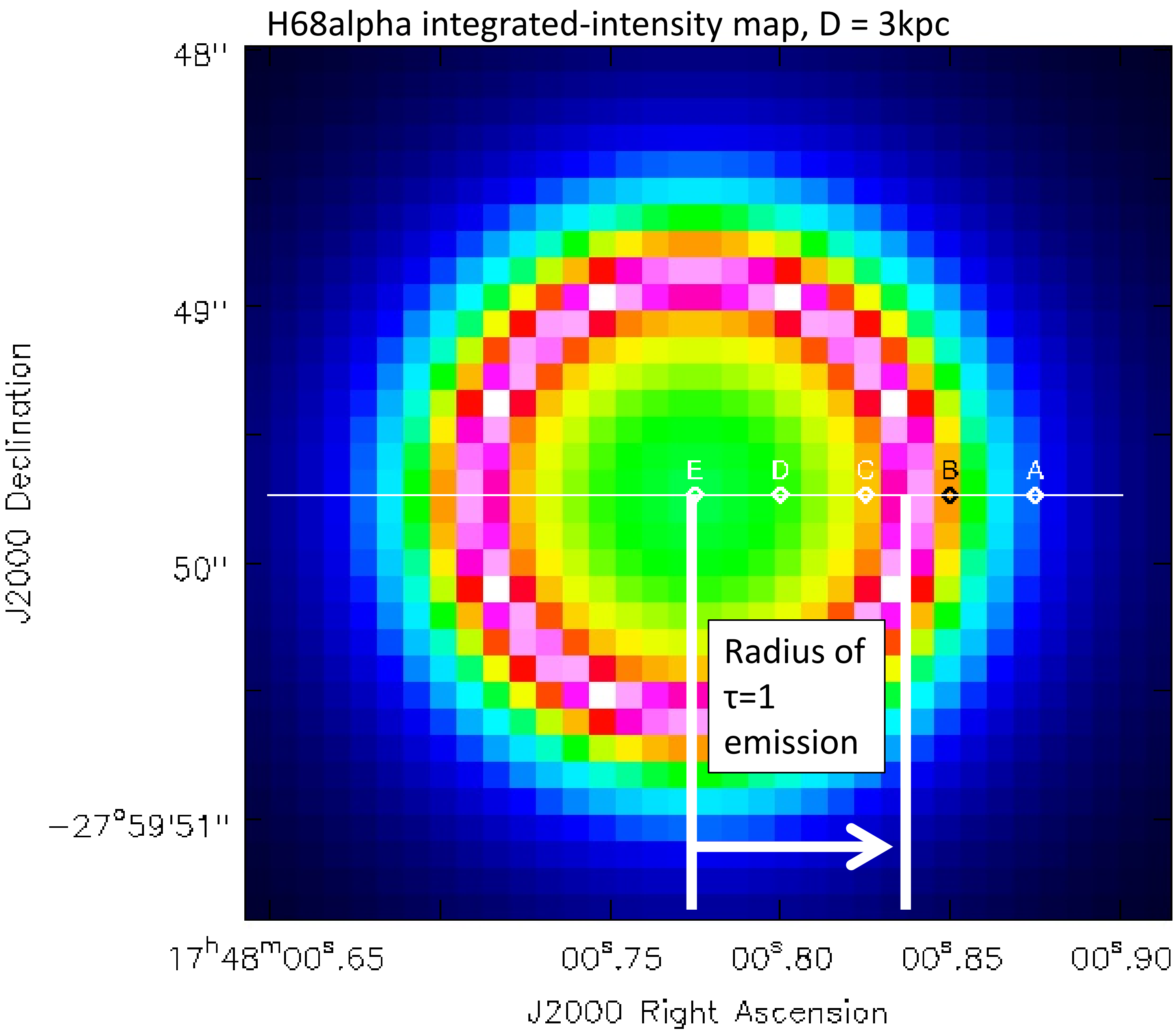
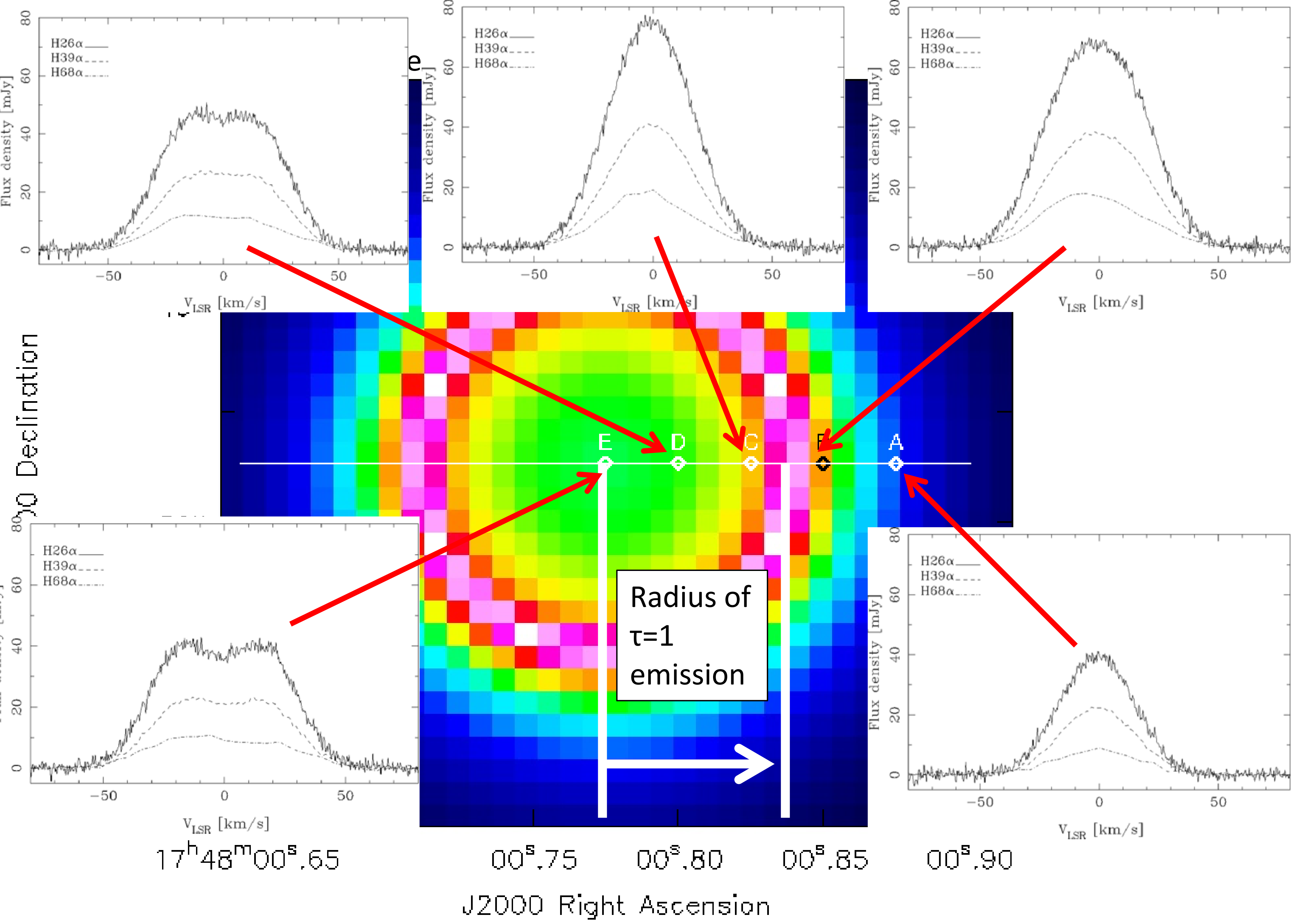
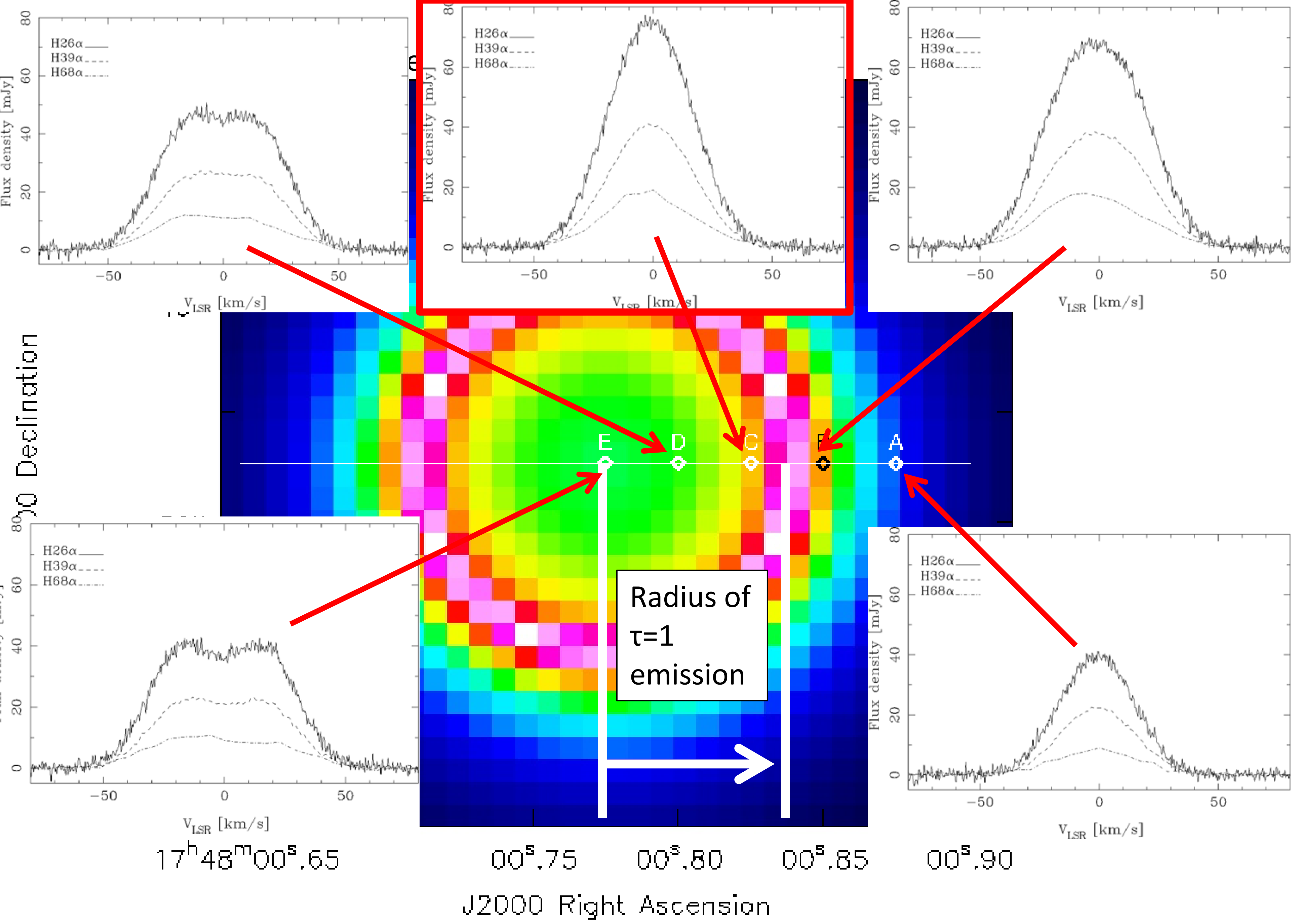


Intensity increases with decreasing radius until emission becomes optically-thick


H68alpha integrated-intensity map, D = 3kpc
48''
49''
50''
−27°59'51''
J2000 Declination
17h48m00s.65
00s.75
00s.80
00s.85
00s.90
J2000 Right Ascension
E
D
C
B
A
Radius of τ=1 emission


H26α
H39α
H68α
Flux density [mJy]
V_LSR [km/s]
E
D
C
B
A
Radius of
τ=1
emission
Declination
17h48m00s.65
00s.75
00s.80
00s.85
00s.90
J2000 Right Ascension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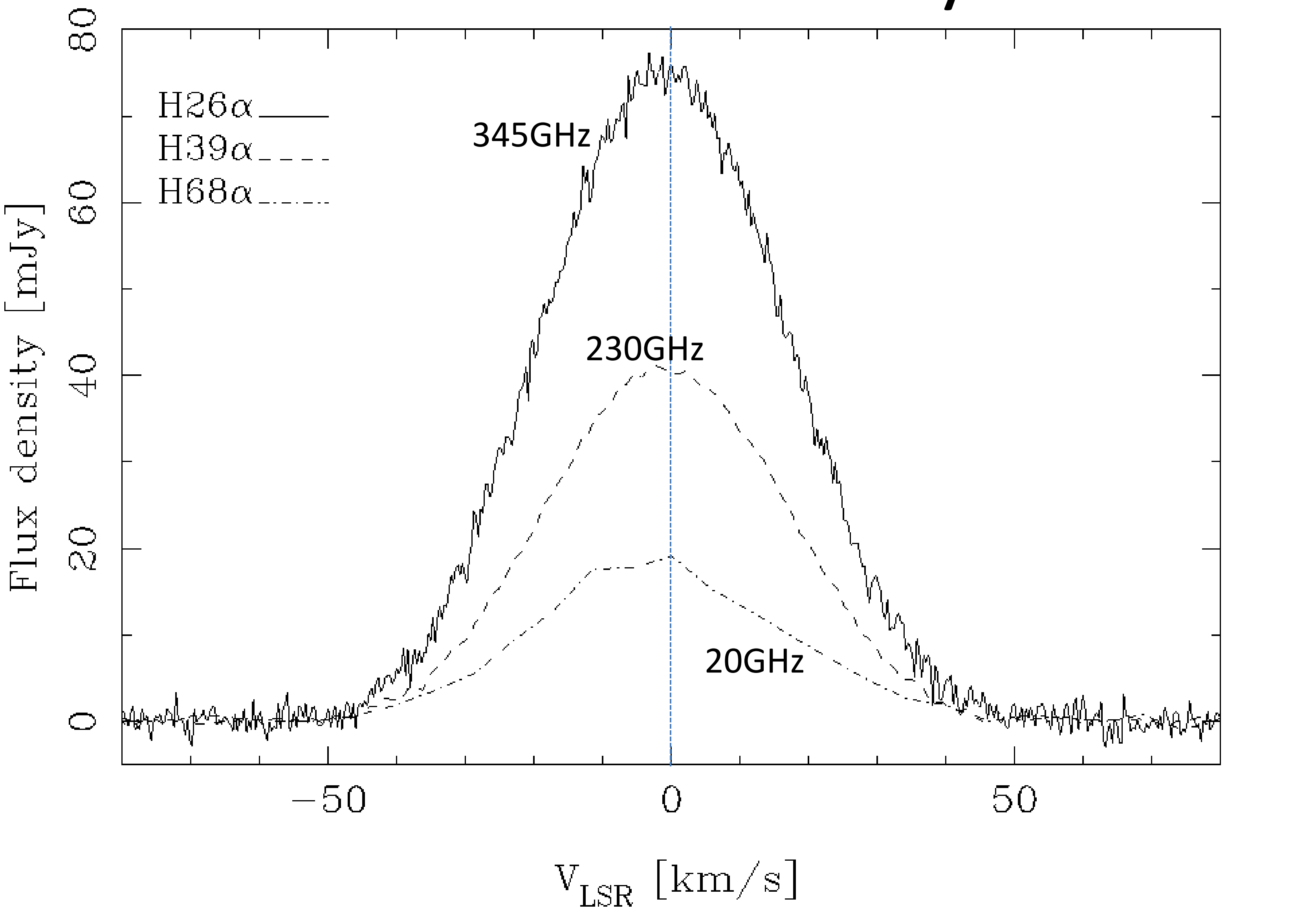
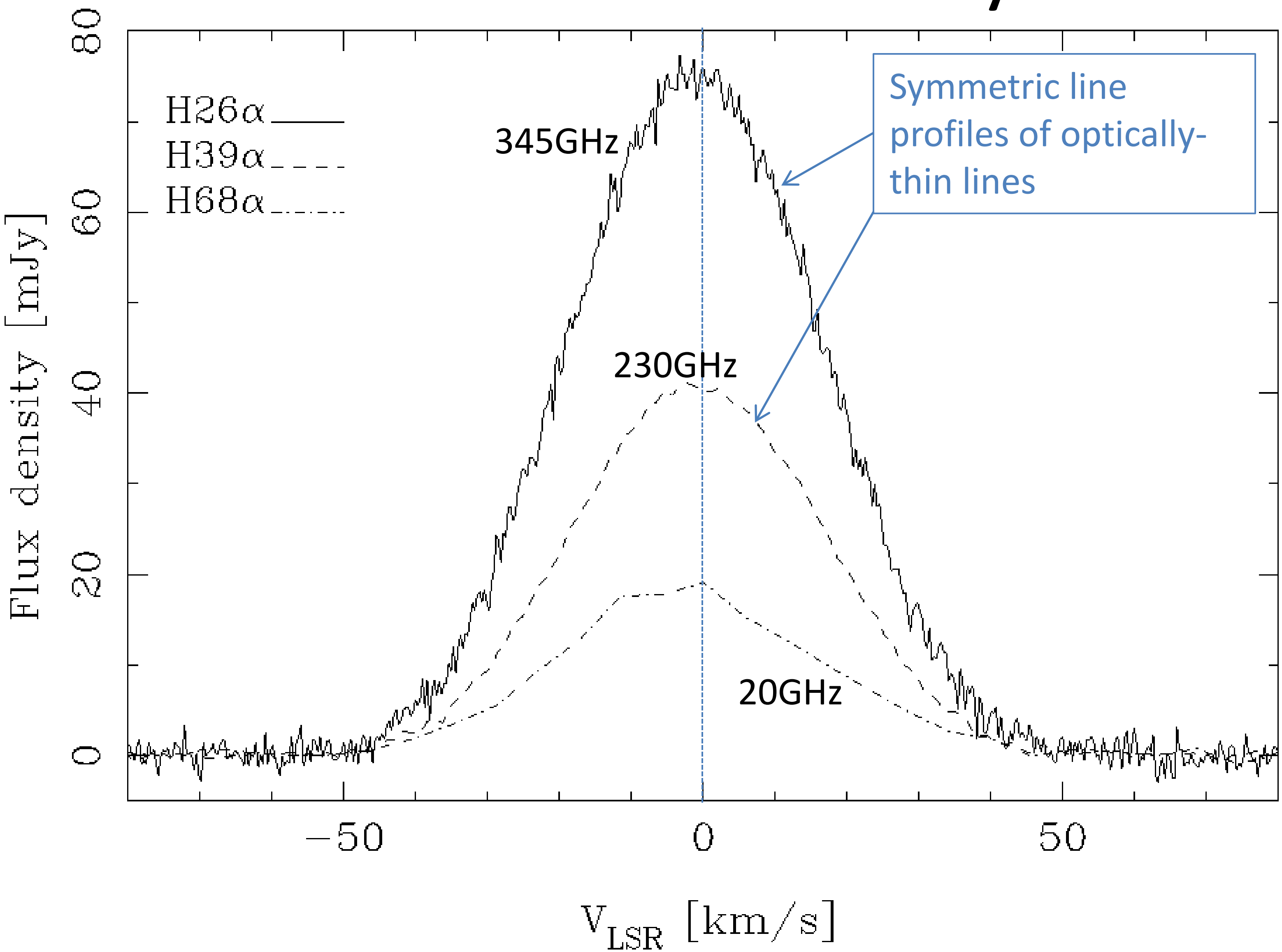
J2000 Right Ascension
J2000 Declination

Compact HII region RRL spectrum at τ = 1 boundary



Compact HII region RRL spectrum at $\tau = 1$ boundary



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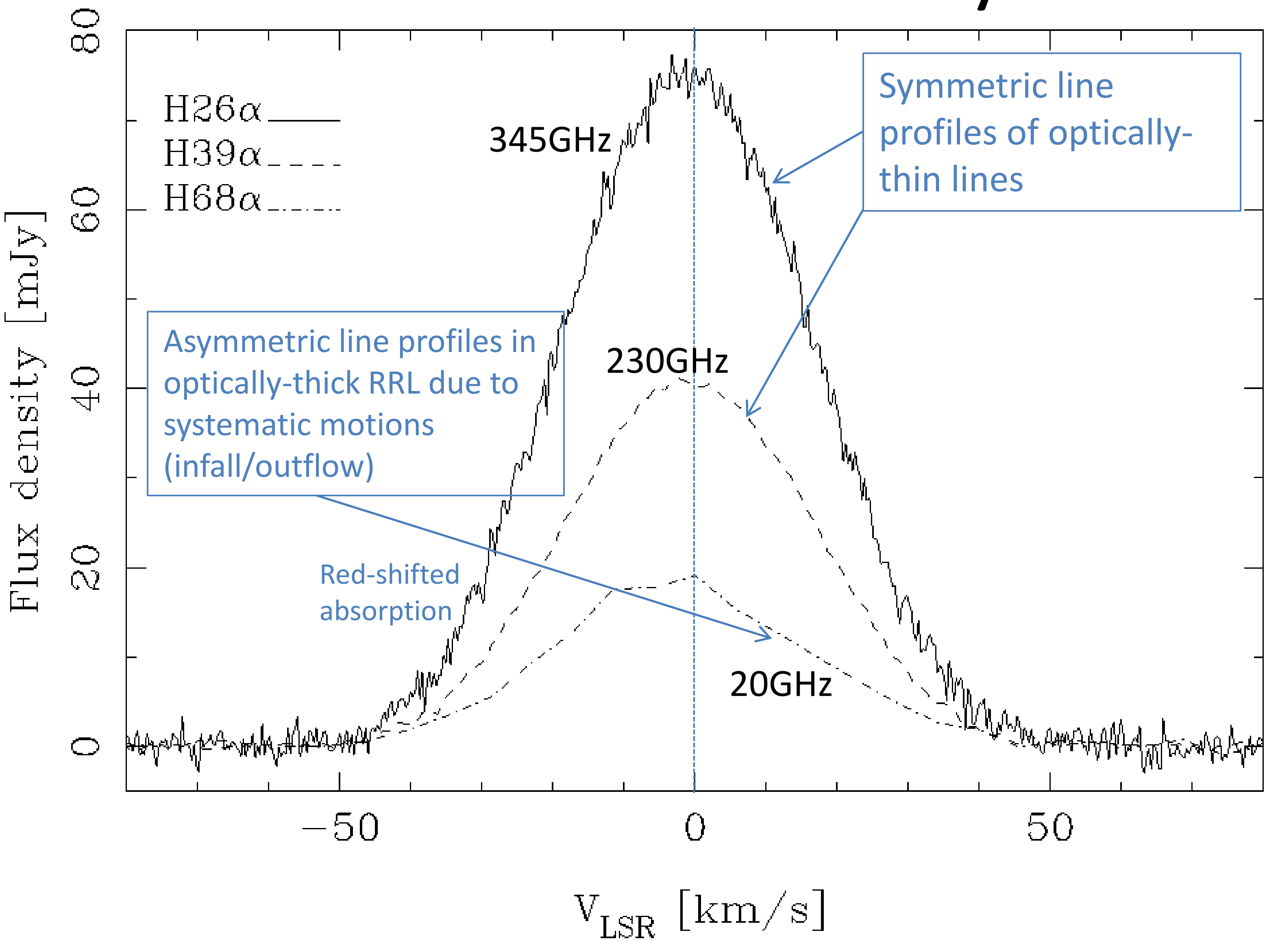

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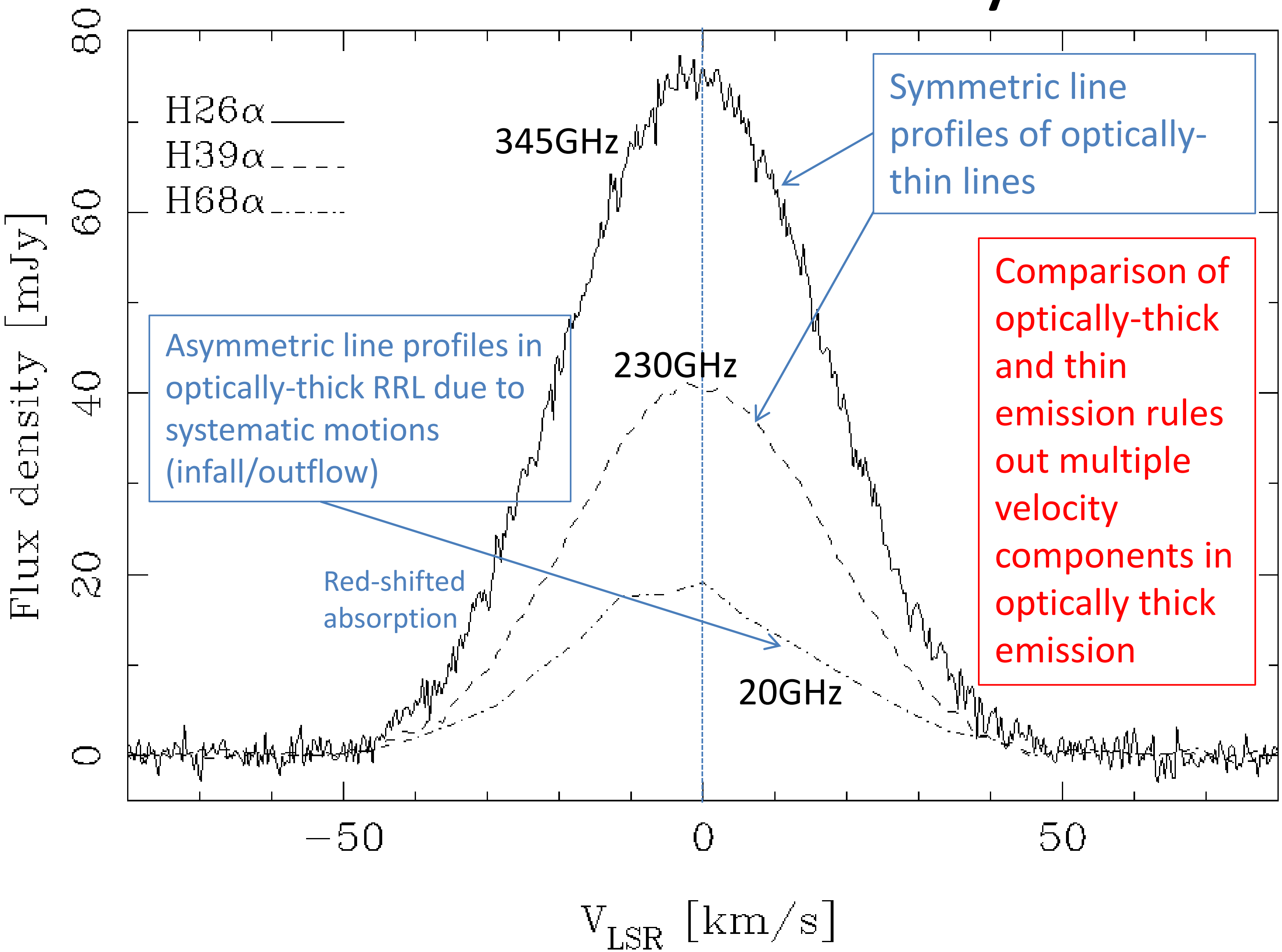
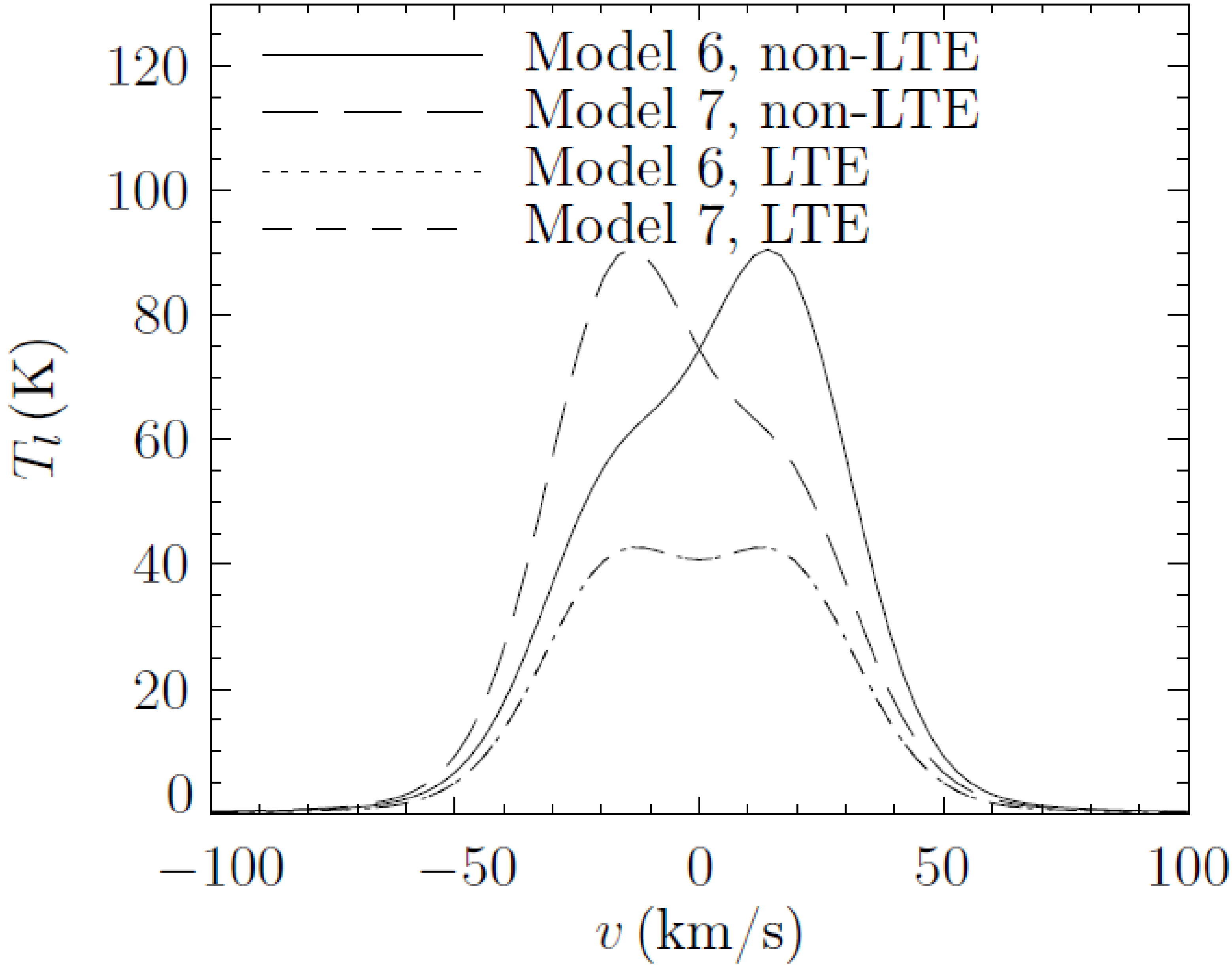
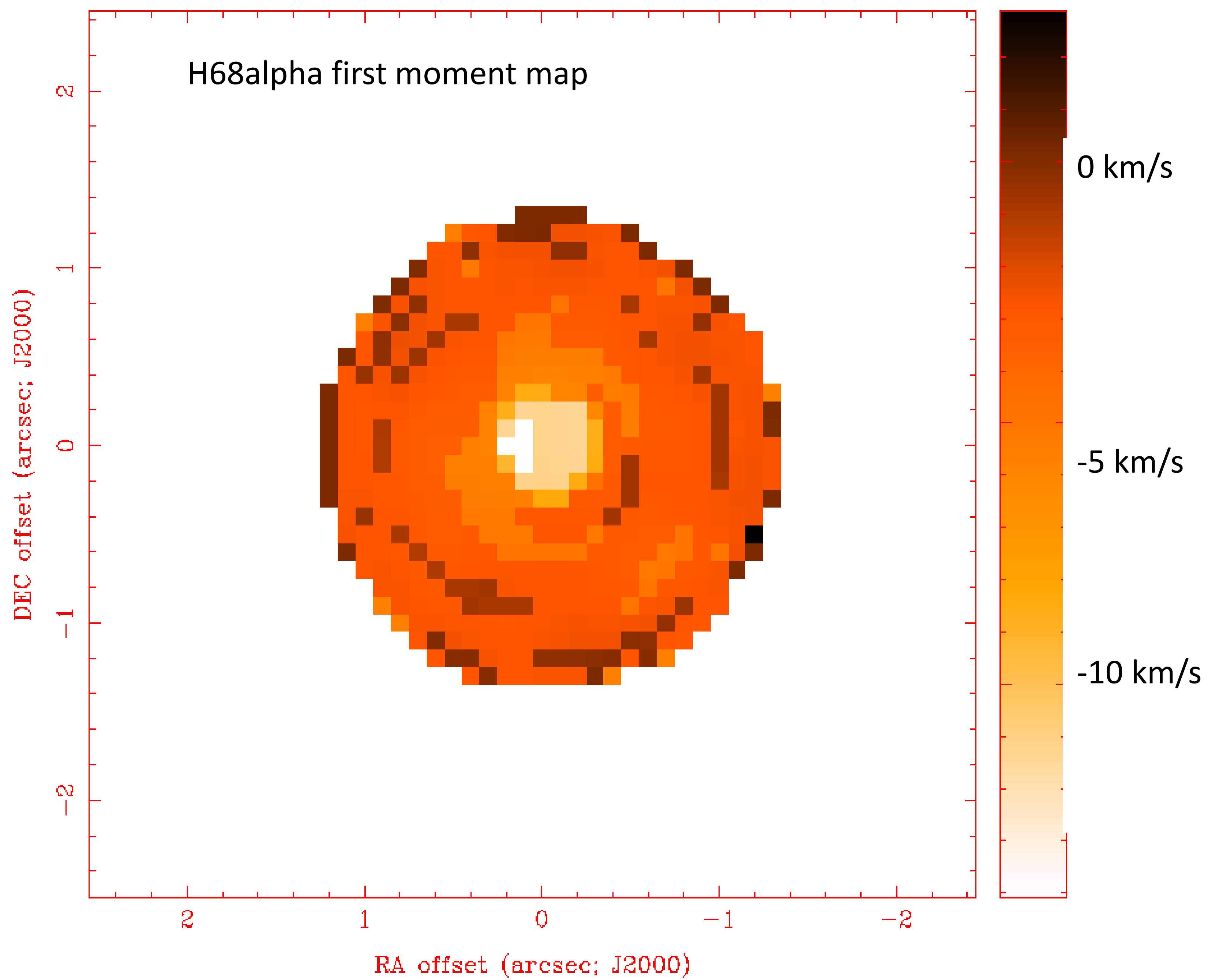
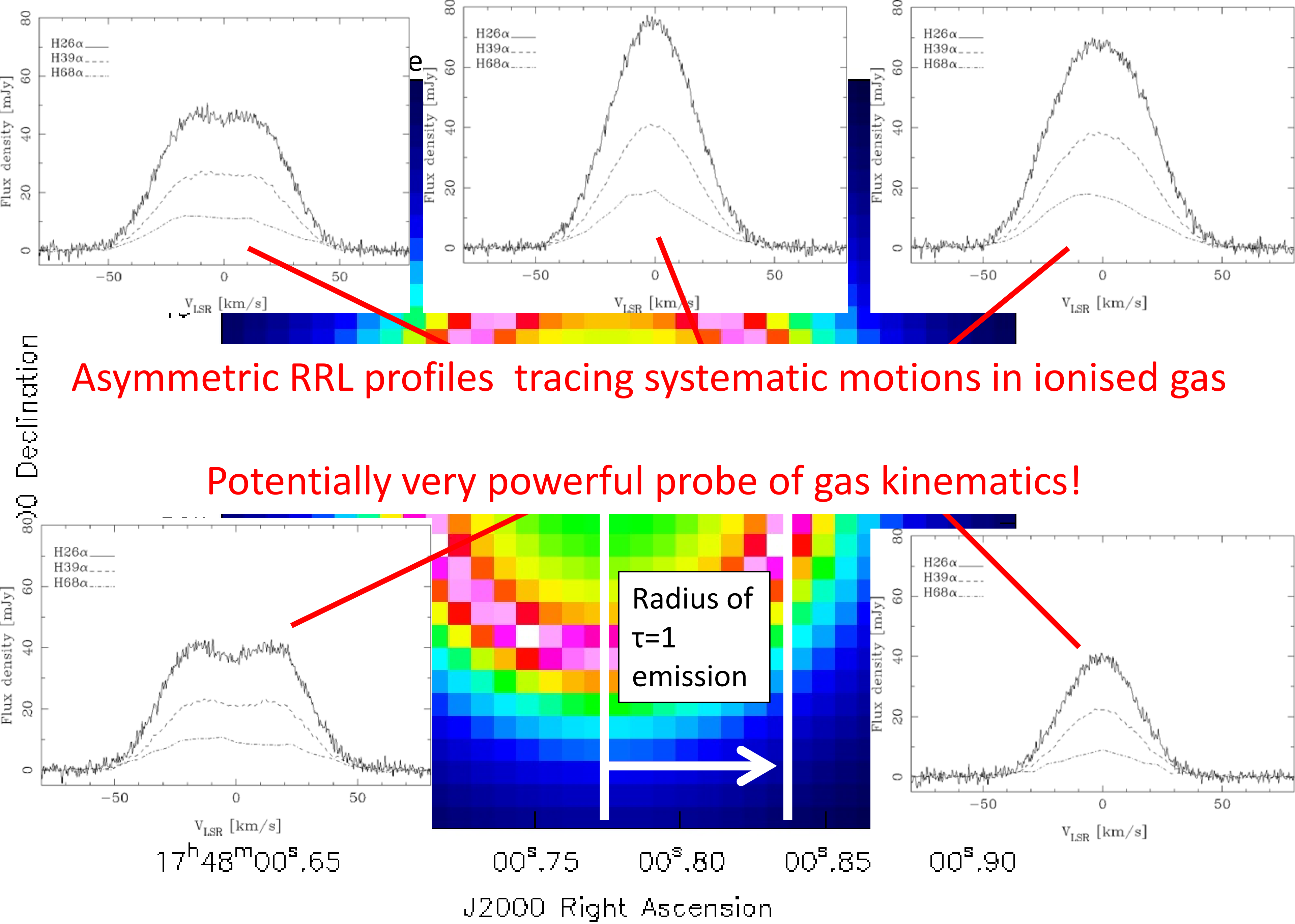


This affect should be very pronounced under the right conditions




H68alpha first moment map
0 km/s
-5 km/s
-10 km/s
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
2
1
0
−1
−2


H26α
H39α
H68α
Flux density [mJy]
V_LSR [km/s]
Asymmetric RRL profiles tracing systematic motions in ionised gas
Potentially very powerful probe of gas kinematics!
Radius of τ=1 emission
17h48m00s.65
00s.75
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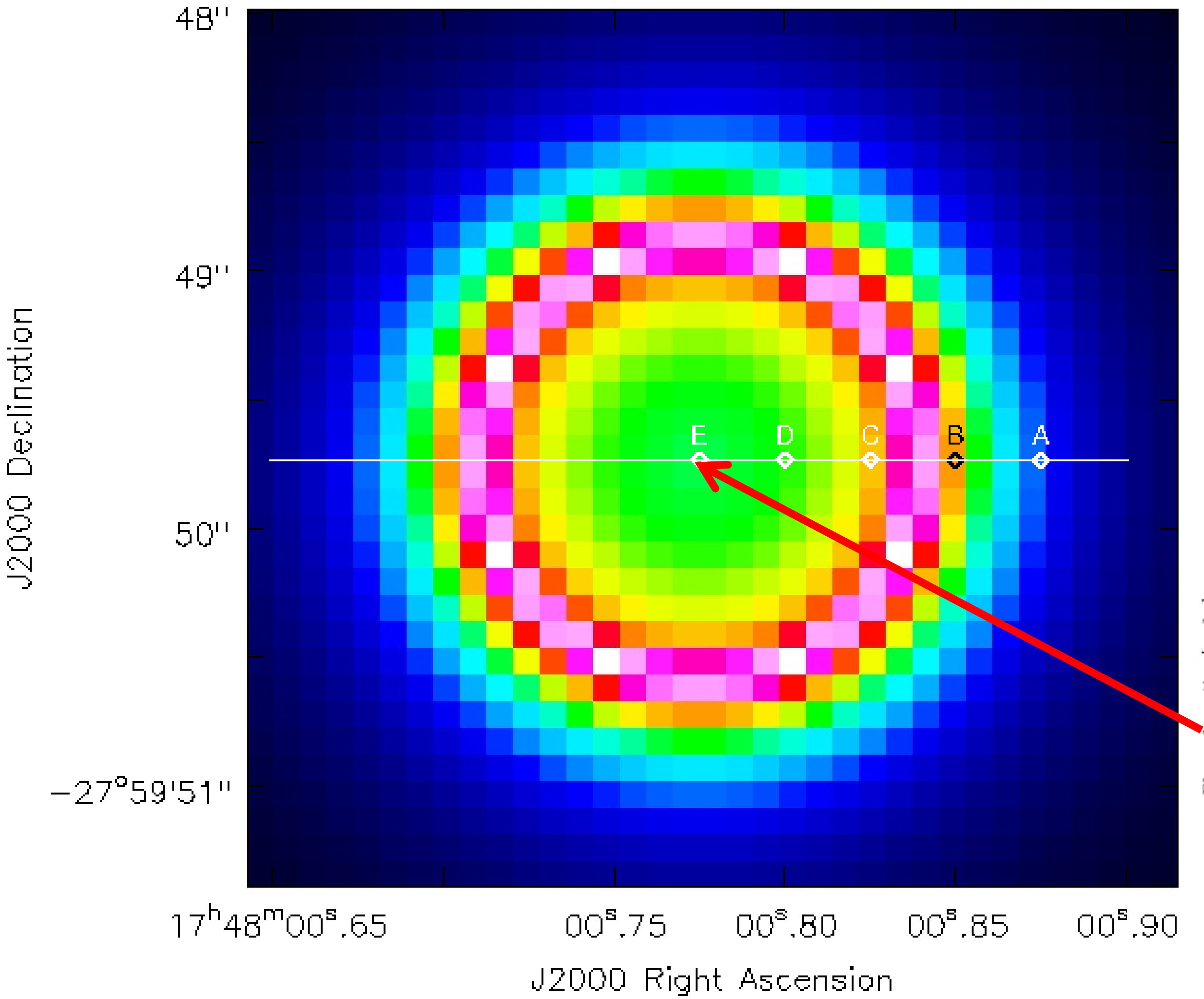
Declination

Under what conditions would we expect to see RRL profile asymmetries?

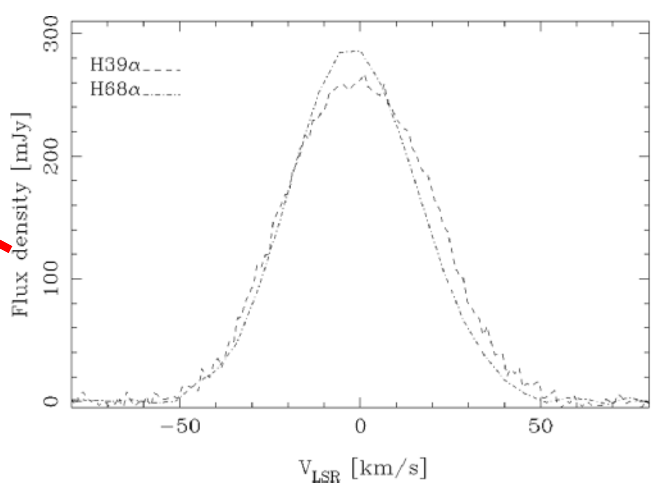
1. Emission must reach $\tau > 1$
2. Resolve optically-thick region
3. Non-LTE conditions: $b_K << 1$
4. Velocity resolution of order the sound speed in ionised gas

C2: resolve optically-thick emission regions

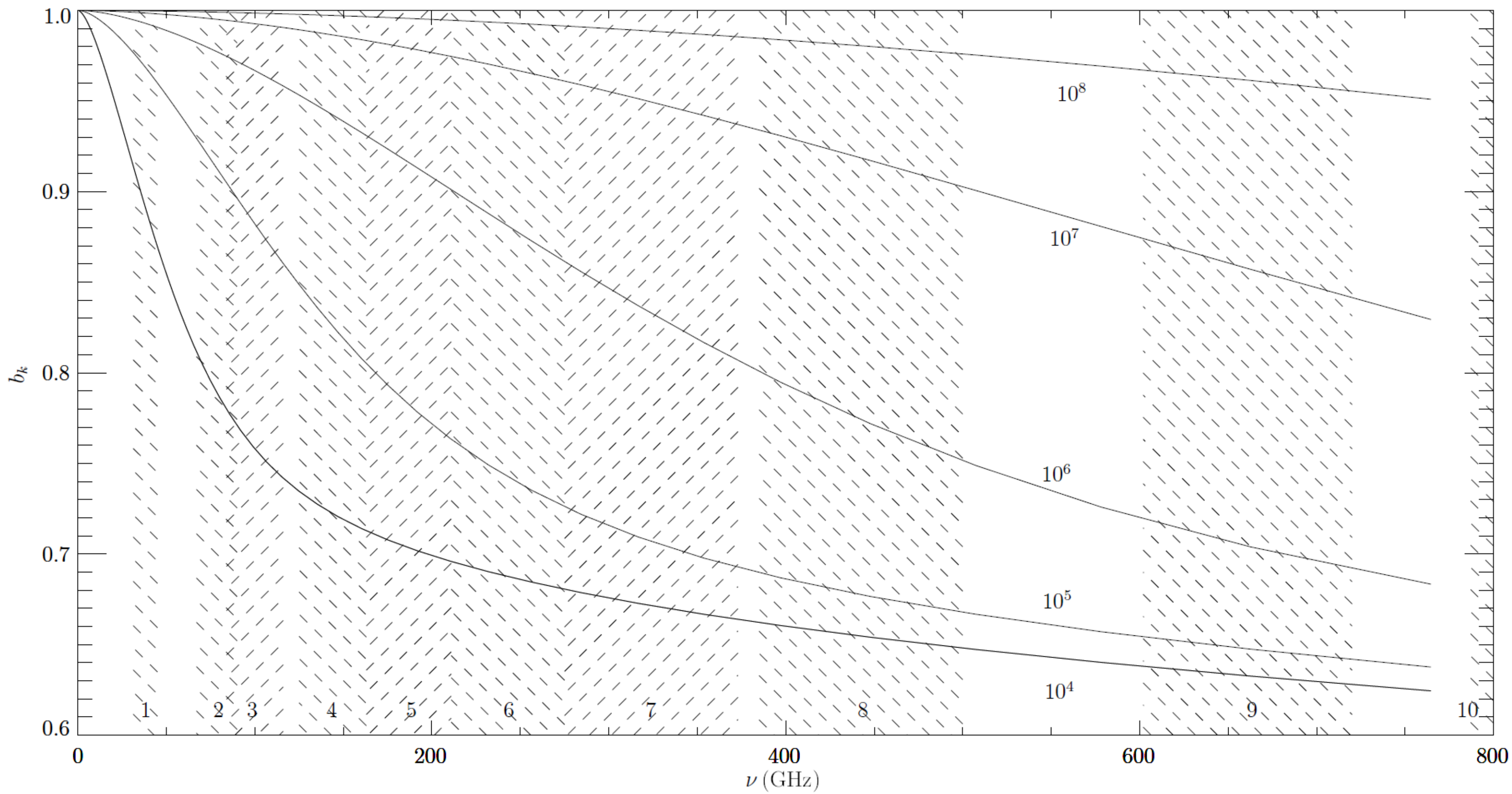


At 1" resolution ➔ can't resolve the optically-thick emission so spectra dominated by optically-thin emission in beam

See no RRL profile asymmetries



C3: b_K ➔ quantifying the departure from LTE conditions



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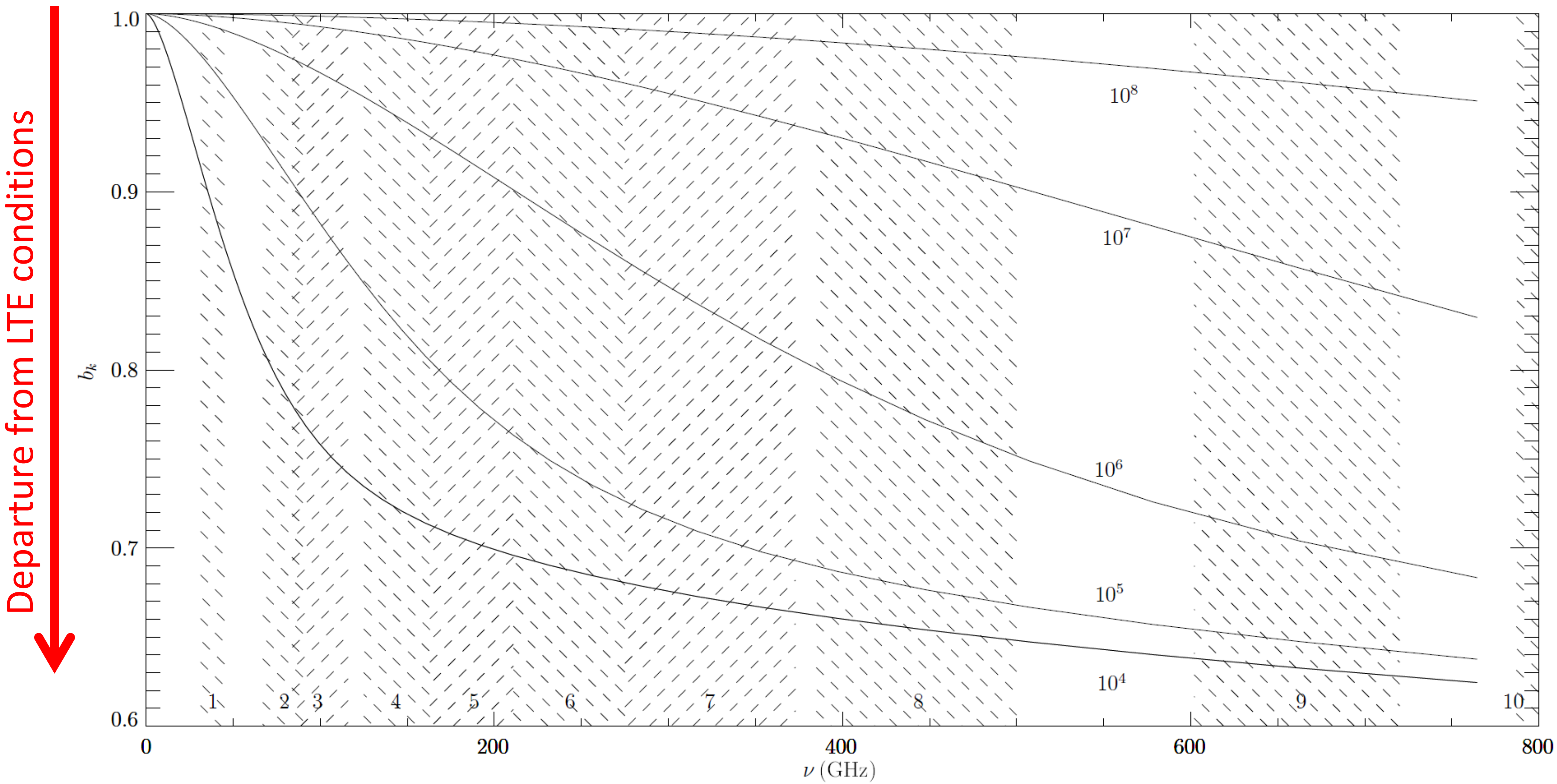

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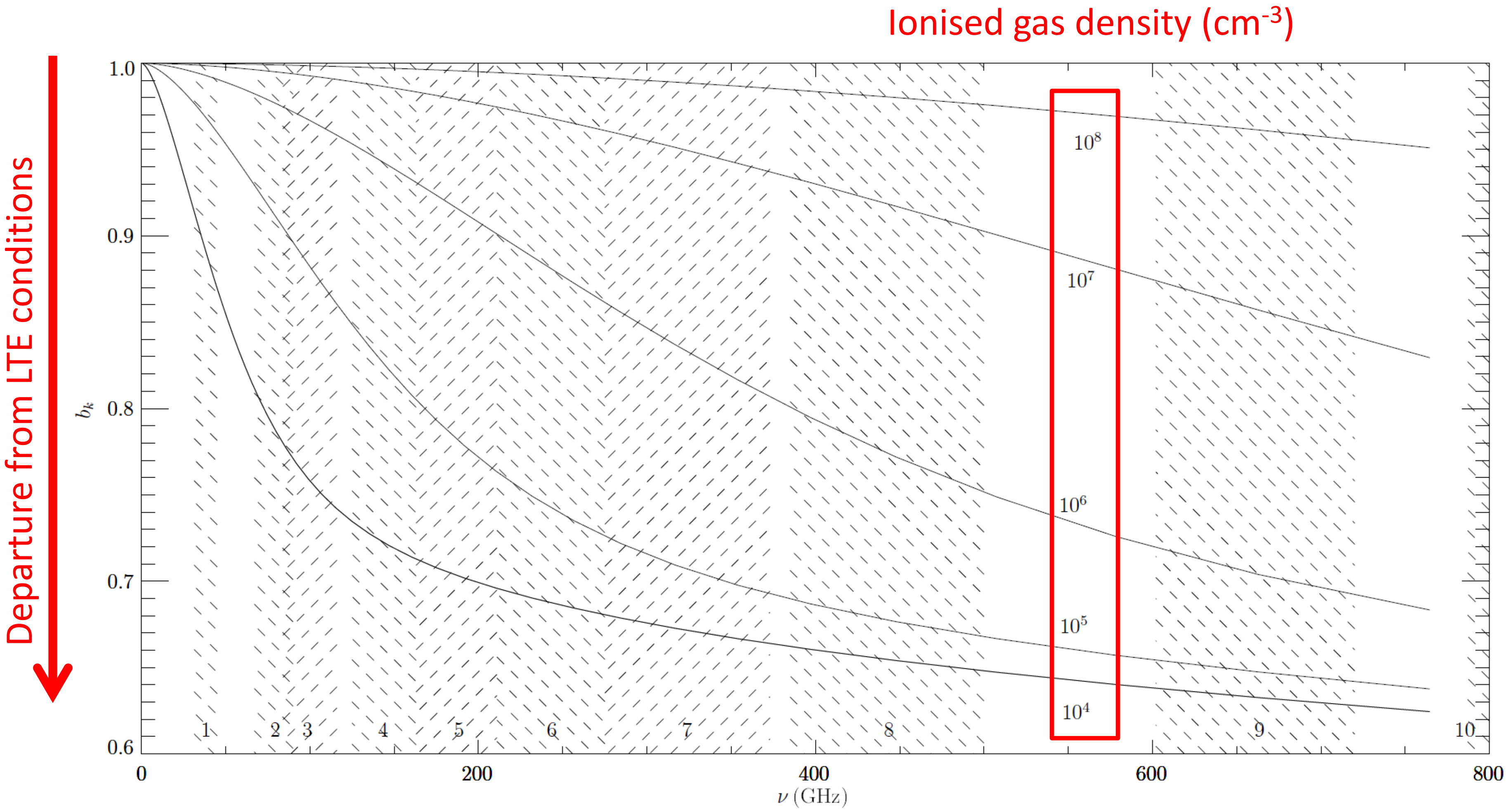

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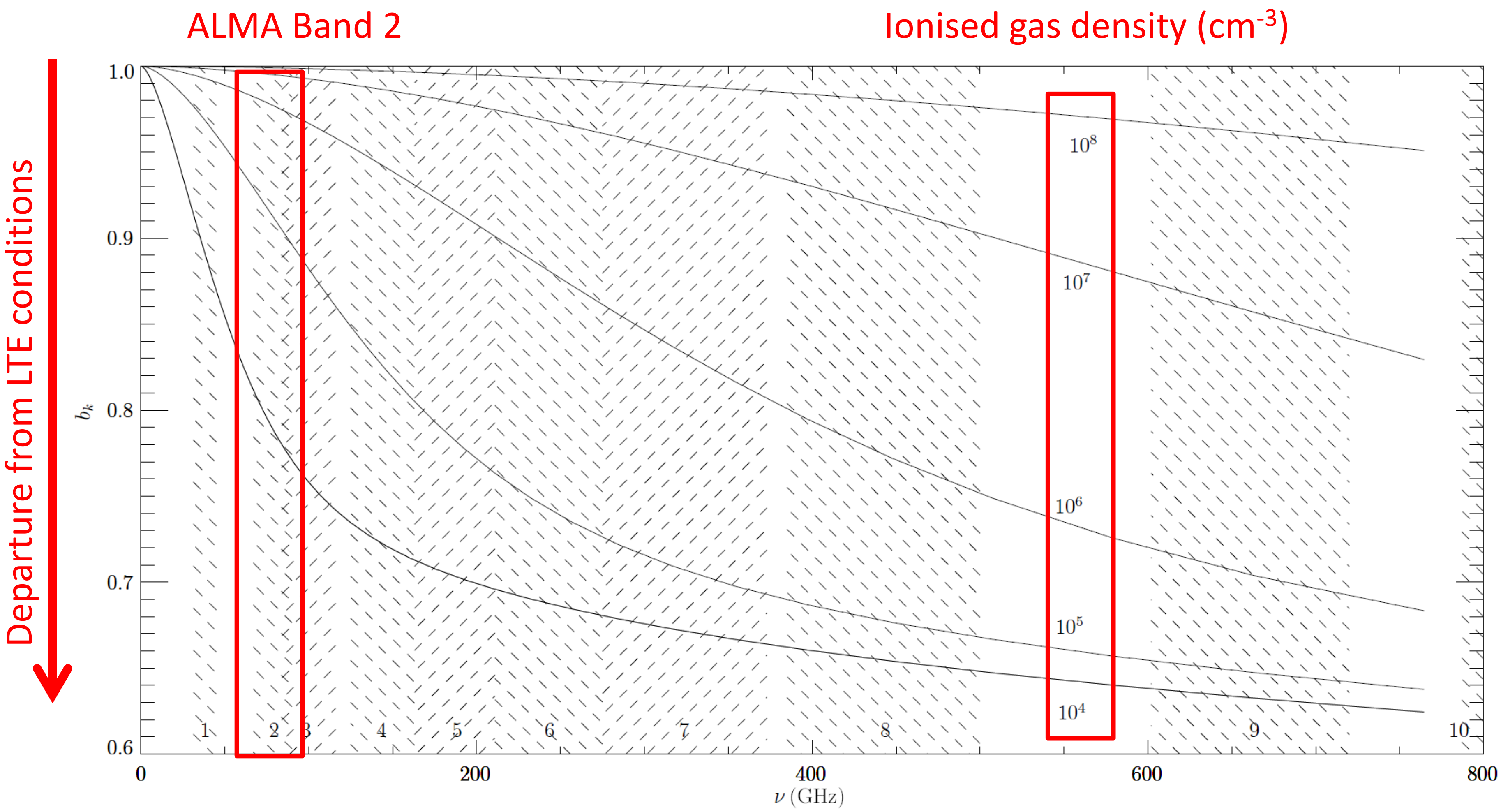

C4: Velocity resolution of order the sound speed in ionised gas

- Intrinsic linewidth of RRL profile composed of two components
  - Pressure broadened component
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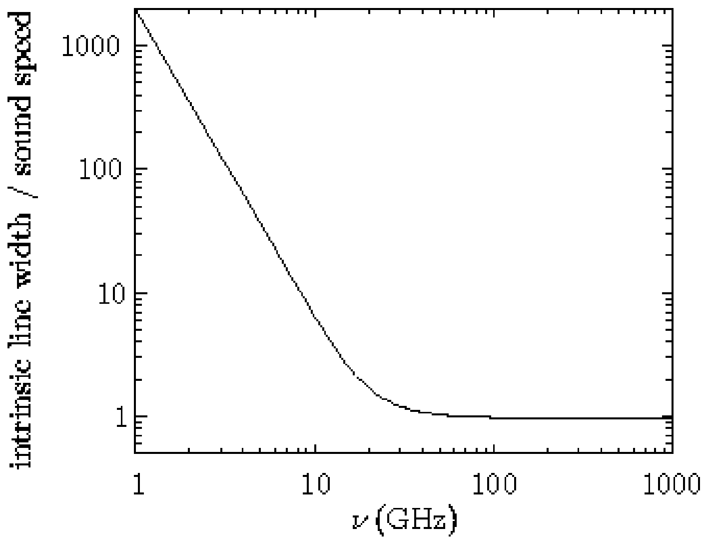

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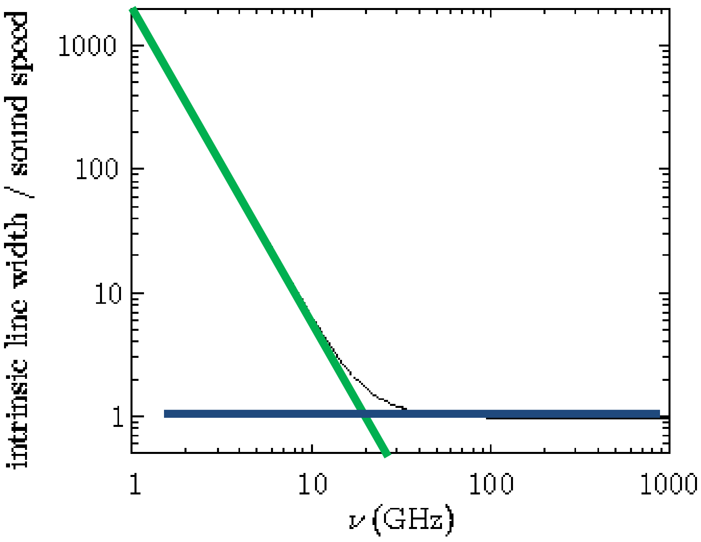

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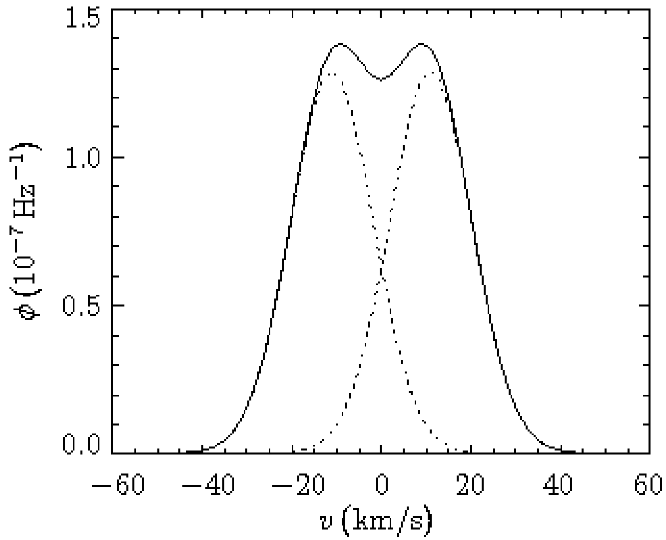
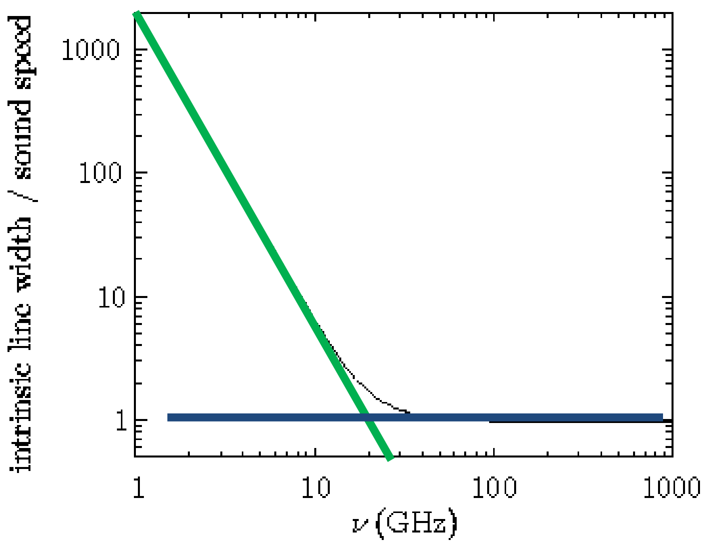


- Asymptotes towards sound speed at high frequency

- To resolve kinematics of ionised gas need velocity resolution of order sound speed



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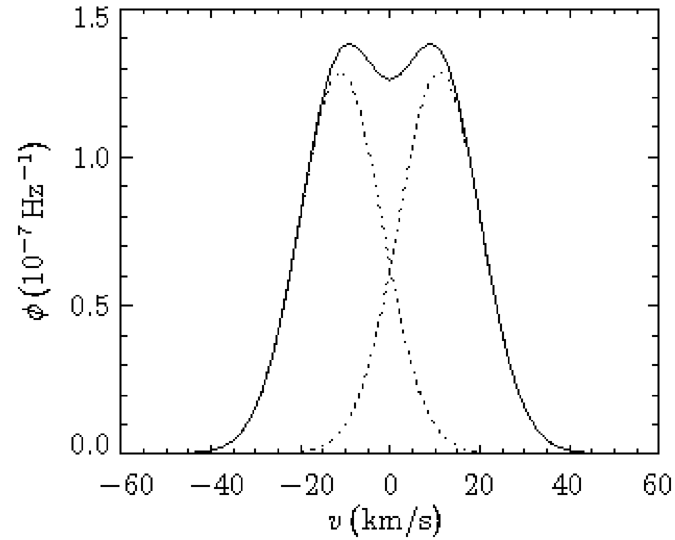

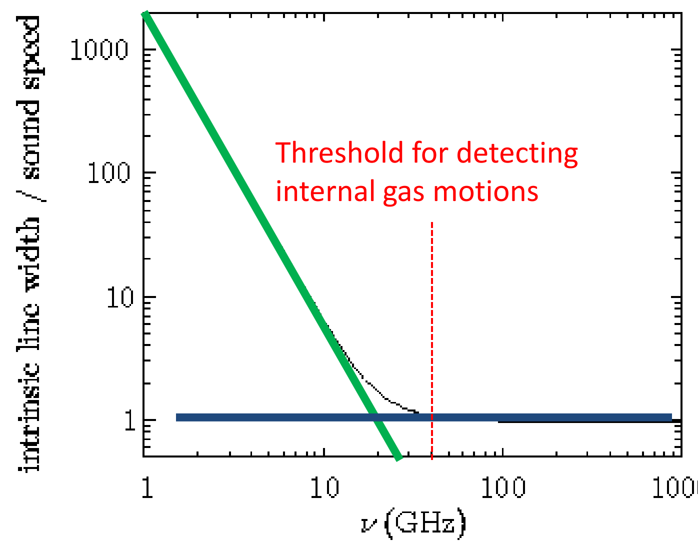

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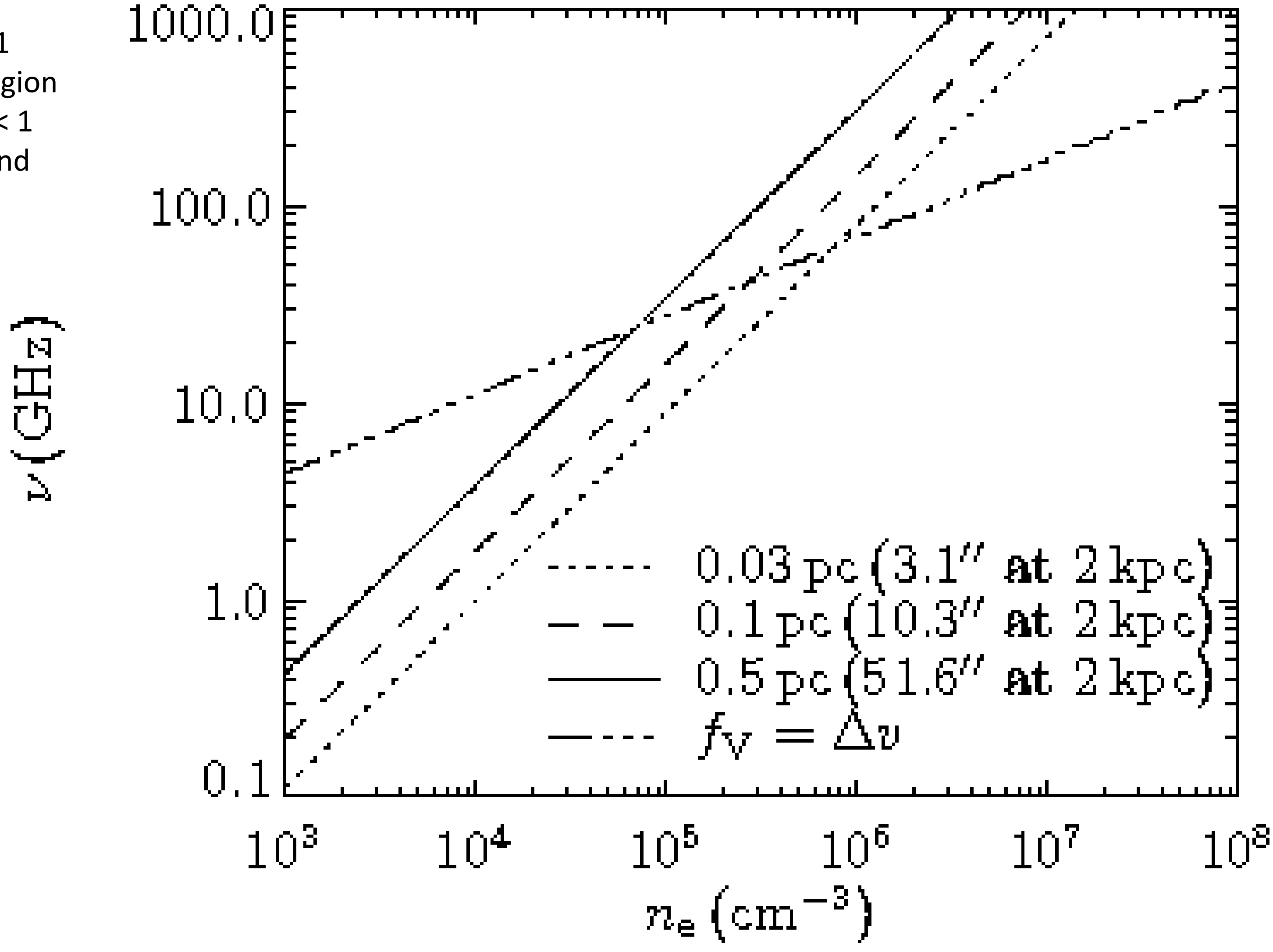

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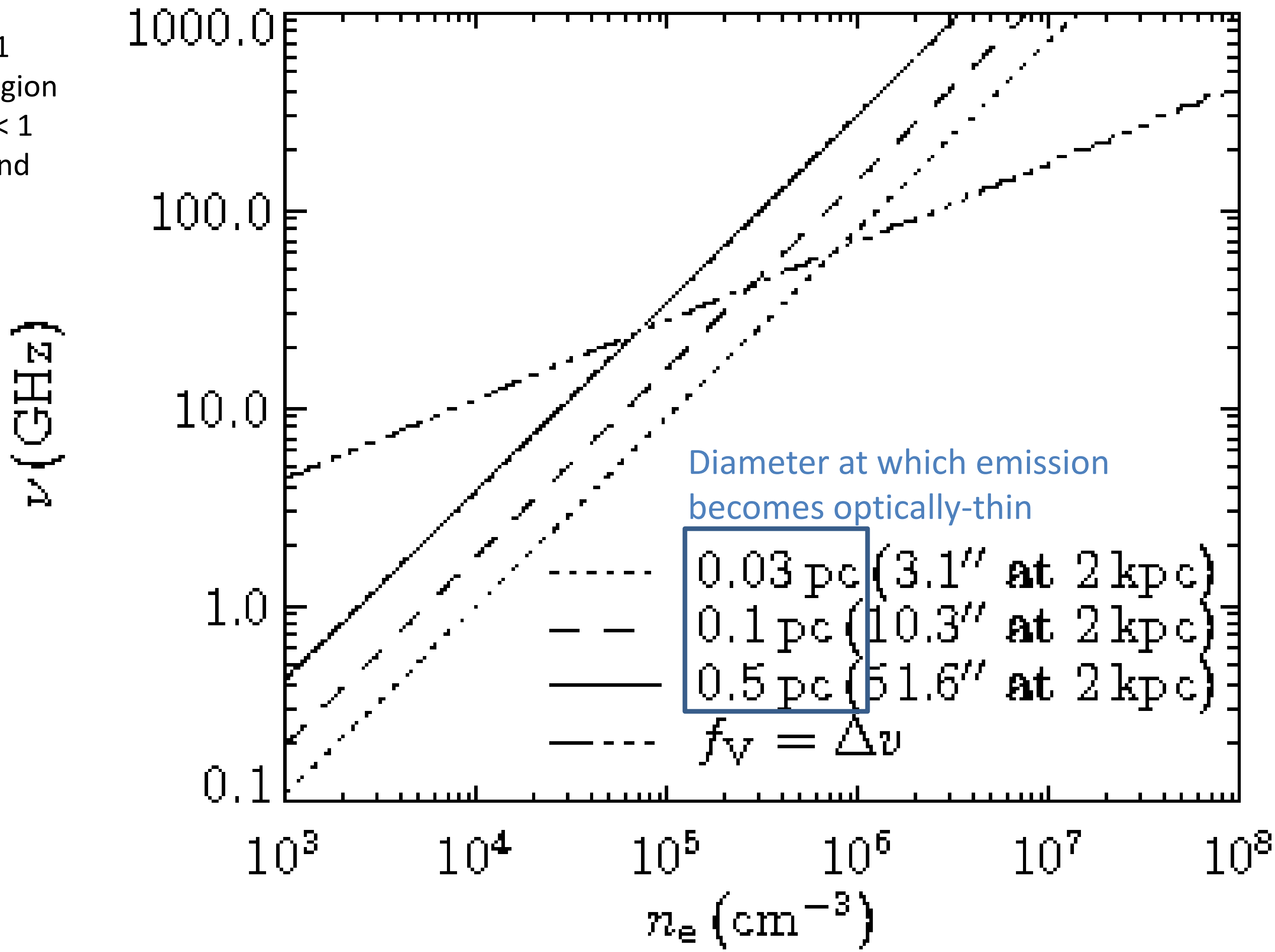

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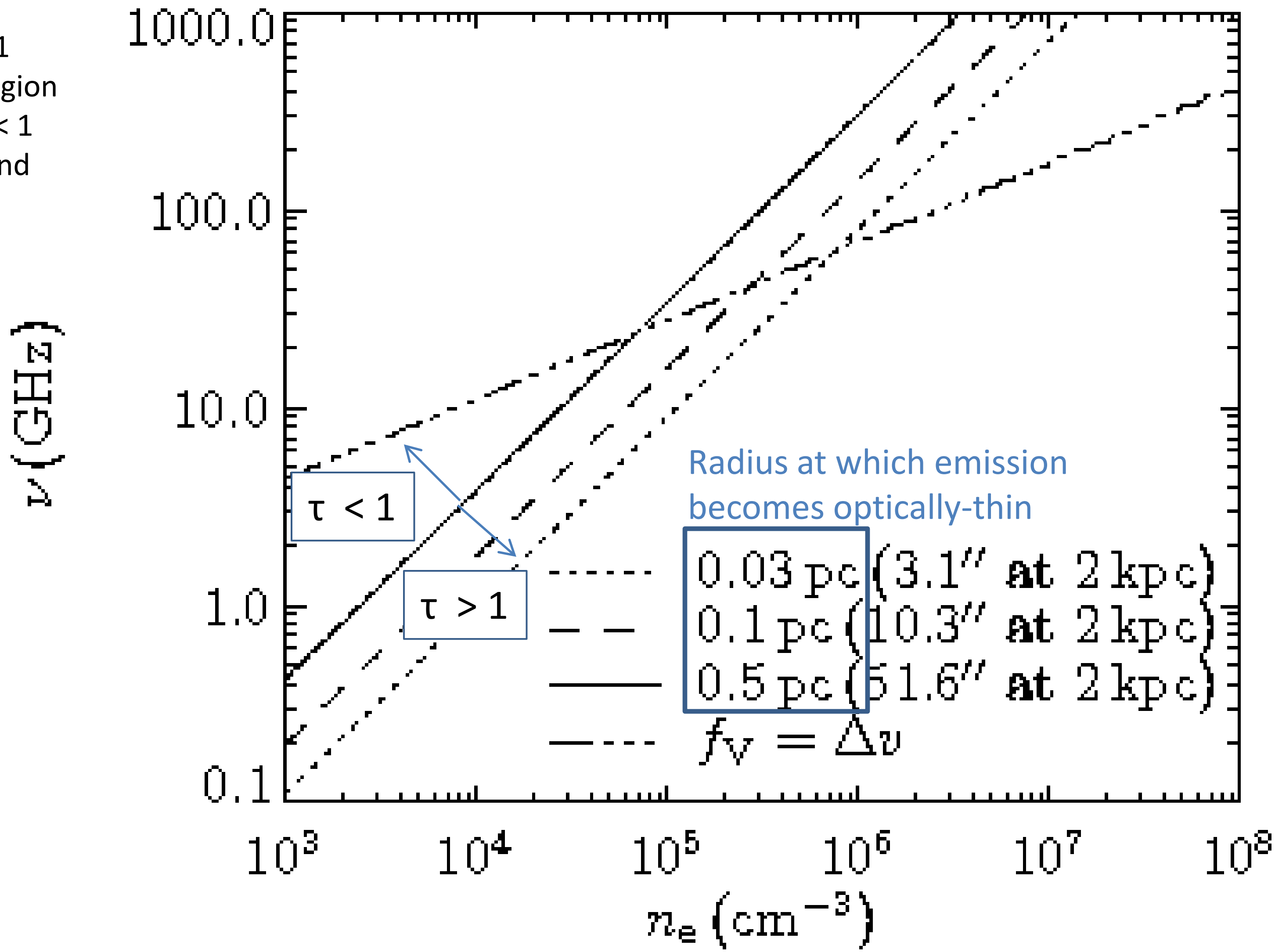

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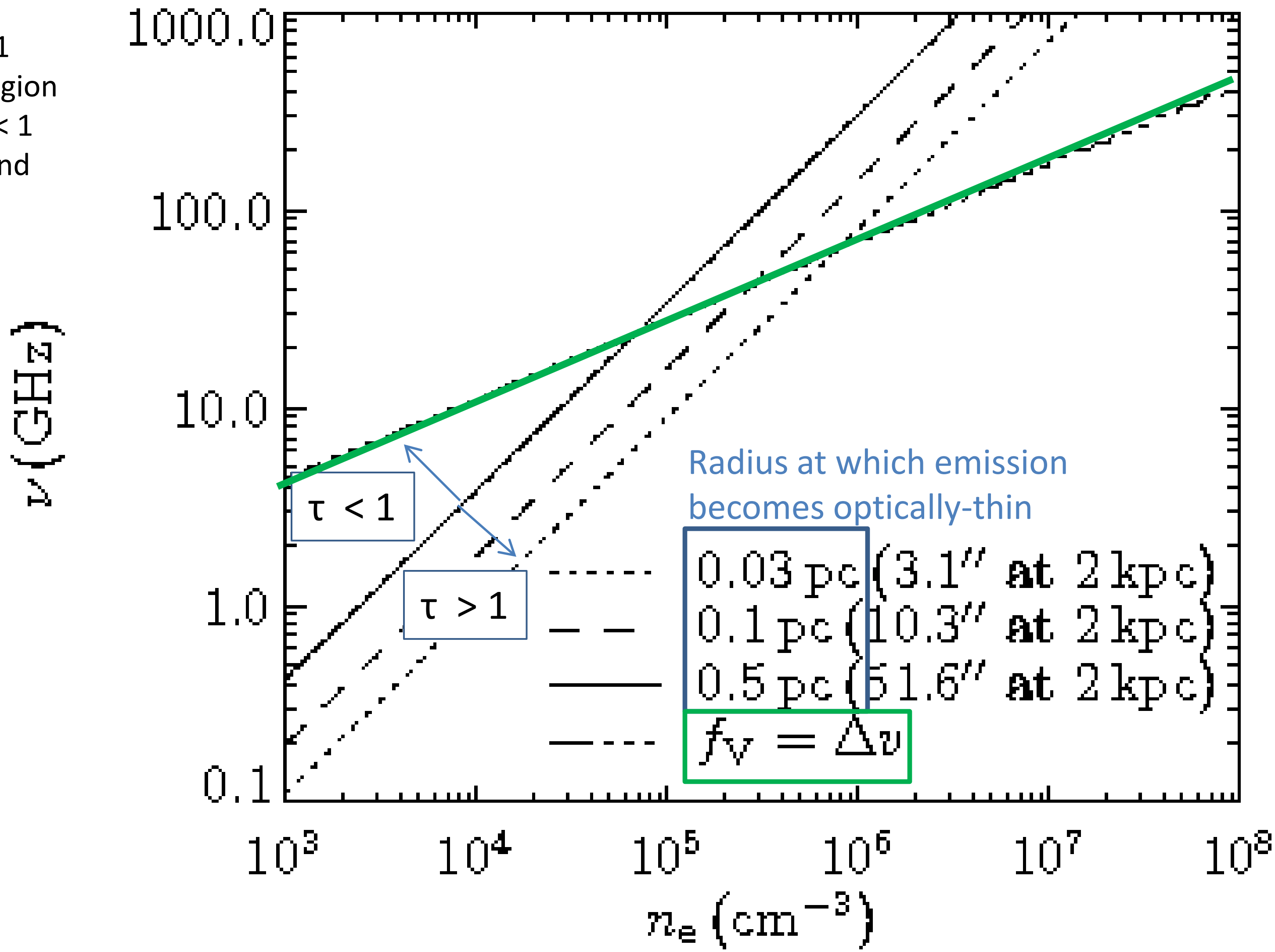

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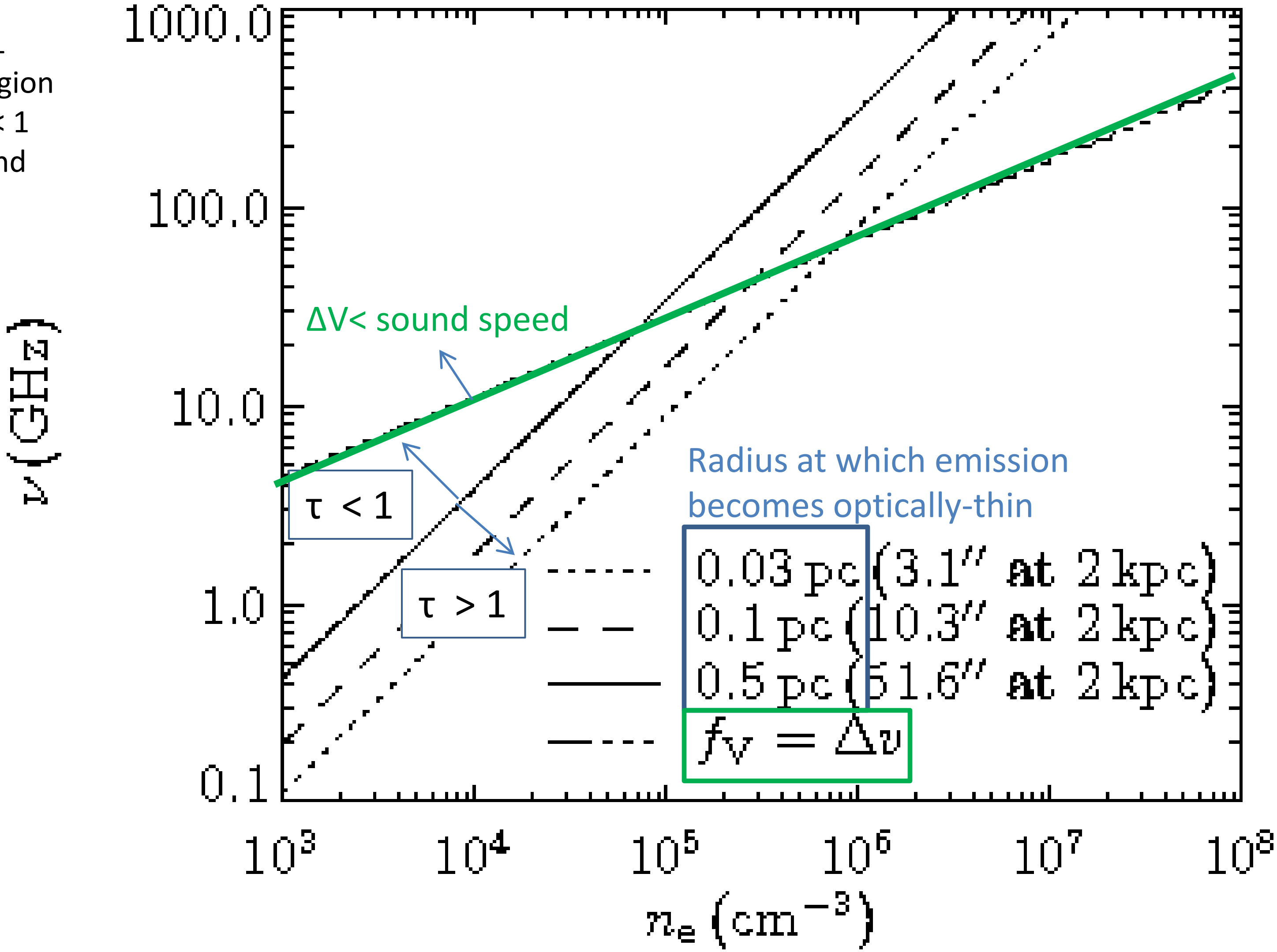

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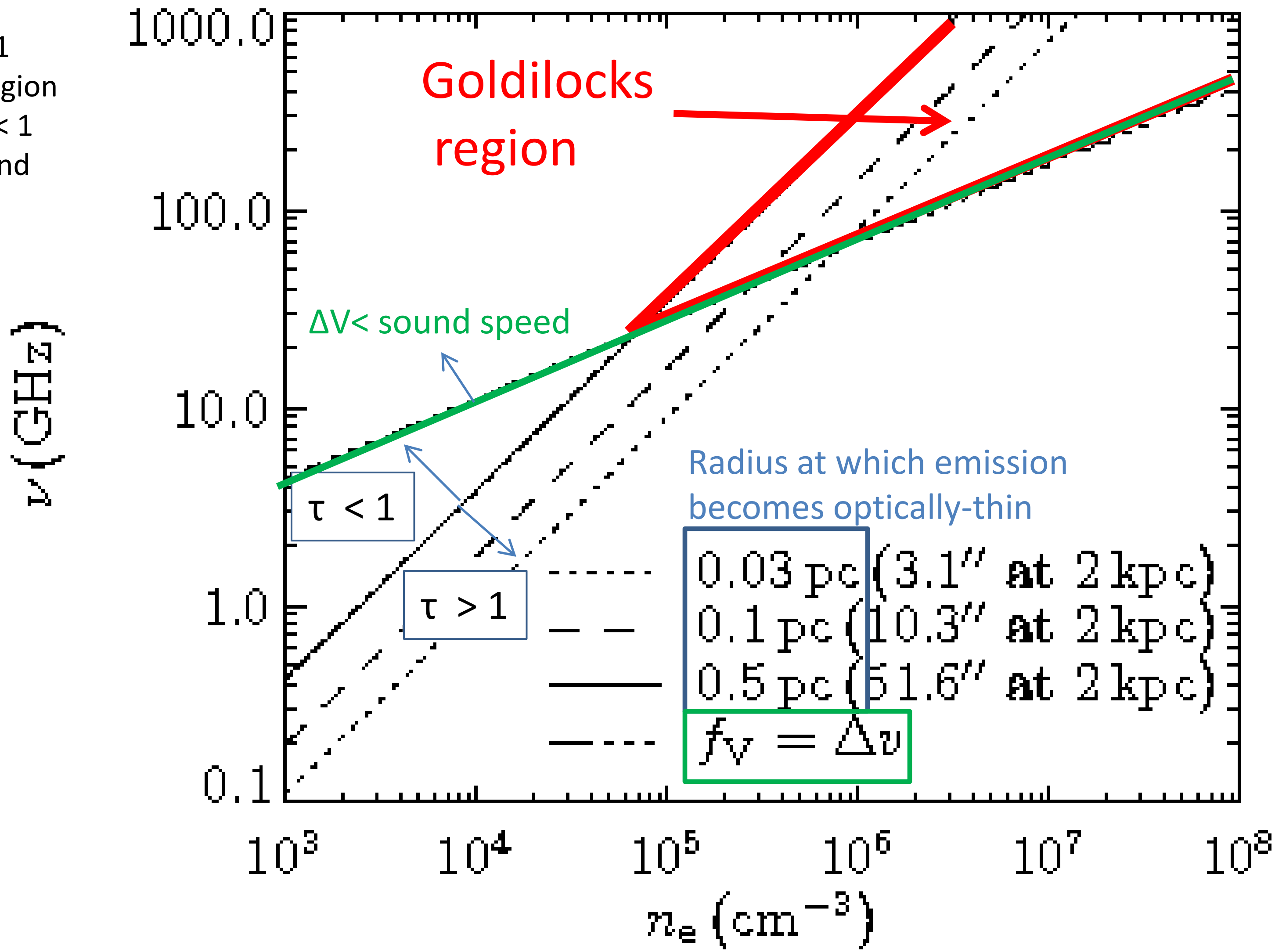

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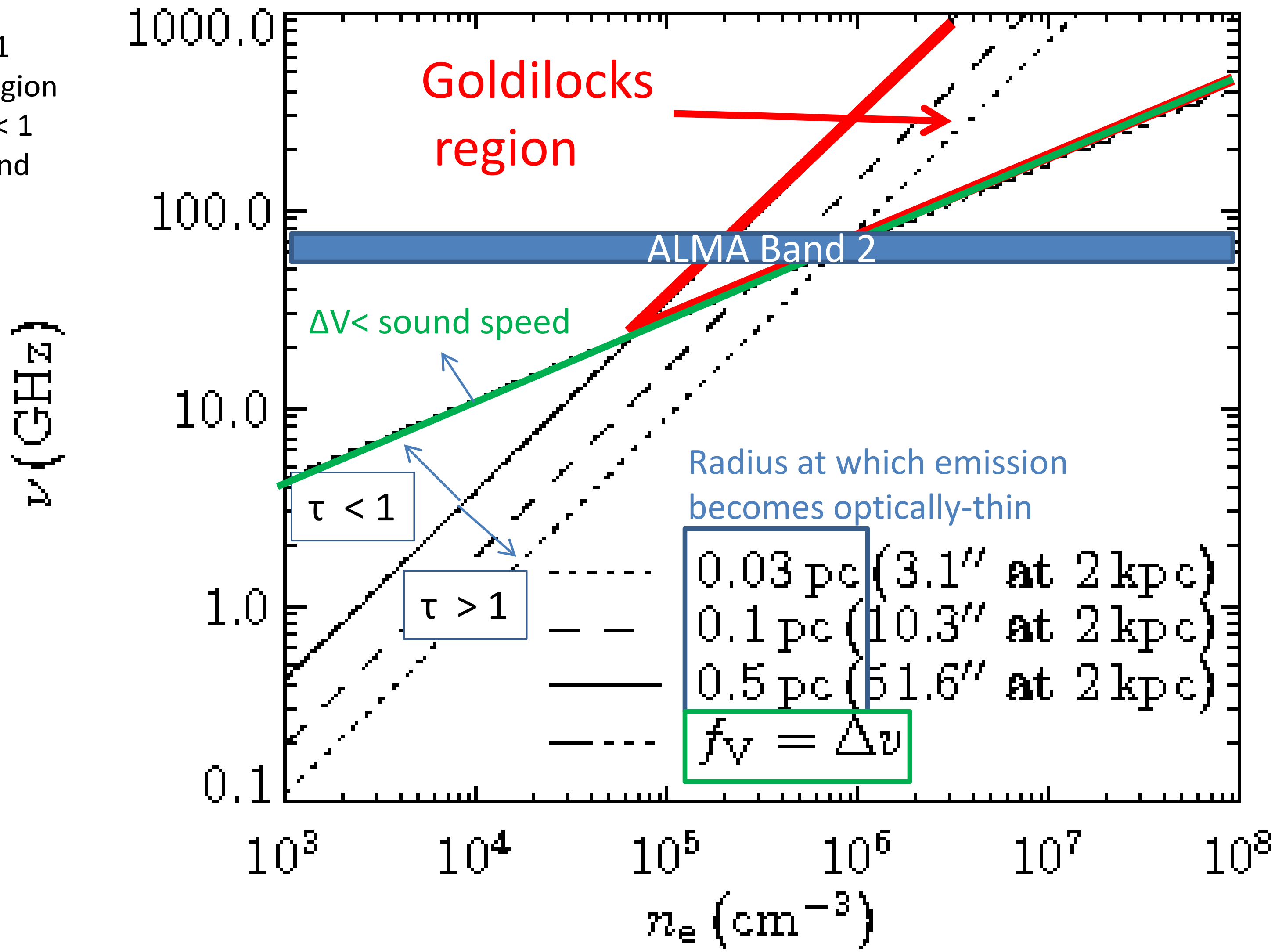

Outline

- Some key open questions in MSF:
  - Where does the mass that eventually end up on a massive star come from?
  - What is the affect of ionisation feedback?

- What do we need to learn to solve these questions?
  - A1: Initial conditions of both core fragments and cluster-scale gas
  - A2: Ionised gas properties and kinematics

- How will ALMA Band 2 help provide the answers?
  - A0: Larger primary beam, combined with ALMA's high angular resolution will allow efficient surveys of massive protoclusters with observations sensitive to the key range in spatial scales
  - A1: Key transitions of deuterated species
  - A2: Optimal frequency for finding youngest HII regions and deriving their physical properties